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Early Cost Estimation of Die Cast Components

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EARLY COST ESTIMATION OF DIE CAST COMPONENTS

BY

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ABSTRACT

An early cost estimation methodology for die cast components has been developed. It is intended for use by product designers before detailed drawings or prototypes have been produced. The purpose of this estimating method is to allow designers to quickly determine the costs of producing die cast components without the need for specific knowledge of the die casting process. This cost can then be used for comparison with other manufacturing methods. This estimation procedure will inevitably expand the designers awareness and knowledge of the die casting process.

The methodology developed requires only the input of parameters that are readily available to the designer at the early concept stage, such as material type and geometric characteristics.

Typical parameter values were assumed in many cases in order to approximate optimum processing conditions. The methodology includes estimation procedures for tooling costs and processing costs. A database of material properties and costs is also included. Estimates obtained by using the methodology were compared with industrial quotes. Statistical analyses of these comparisons indicate that reasonably accurate results were obtained.

ACKNOWLEDGEMENTS

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NOMENCLATURE

α	thermal diffusivity, mm^2/s
η	die casting machine efficiency factor, dimensionless
ρ	material density, Mg/m^3
a	half casting wall thickness, mm
A_{pc}	projected area of cavities, mm^2
A_{pf}	projected area of feed system, mm^2
A_{ph}	hydraulic piston head area, mm^2
A_{pl}	platen area, mm^2
A_{plt}	plunger tip area, mm^2
A_{po}	projected area of overflow wells, mm^2
A_{pr}	projected area of runners, mm^2
A_{ps}	projected area of shot envelope, mm^2
A_{psb}	projected area of sprue or biscuit, mm^2
A_{pt}	total projected area of molten metal within the die, mm^2
b_d	minimum casting machine rate, $/hr
C_a	alloy cost for each casting, $
C_d	cost of a single-cavity die casting die, $
C_{dn}	multi-cavity die casting die cost, $
C_m	die casting machine cost, $
C_p	specific heat , J/kg*°C
C_{rd}	die casting machine and operator rate, $/hr

C_{rt}	trim press and operator rate, \$/s
C_t	cost of a single-aperture trim die, \$
C_{tn}	multi-aperture trim die cost, \$
CA	total alloy cost, \$
CDC	die casting processing cost, \$
CDS	cost of the die set, \$
CPP	custom punch points
CT	total cost, \$
CTR	trimming processing cost, \$
d_{op}	die opening distance, mm
d_p	plunger tip diameter, mm
d_{ph}	hydraulic piston head diameter, mm
d_s	maximum depth of the shot, mm
DC	total trimming die cost, \$
f	separating force on one cavity, kN
F_1	injection system force, kN
F_c	die casting machine clamp force, kN
F_m	force of molten metal on die, kN
h	interface heat transfer coefficient, $kW/m^2*°C$
H_f	latent heat of fusion, kJ/kg
k	thermal conductivity, W/m*°C
K	die punch constant
l_c	length of shot cylinder, mm
L	length of rectangular shot envelope, mm
m	multi-cavity/aperture die cost exponent
m_1	slope of casting machine rate line, \$/kN
m_d	multi-cavity die cost exponent

m_t	multi-aperture trim die cost exponent
MVP	manufacturing point value
n_c	number of cavities
NT	total number of components to be cast
NUM_{cp}	number of custom punches
NUM_{dsp}	number of different standard punches
NUM_{sp}	total number of standard punches
P_{cp}	total periphery of custom punches, mm
P_h	hydraulic cylinder pressure, MPa
P_m	molten metal pressure, MPa
PAP	punch area points
Q	heat, J
R1	ratio of basic casting cost to tool cost including trimming cost
R2	ratio of basic casting cost to tool cost excluding trimming cost
SPP	standard punch points
t	time elapsed, s
t_c	cooling time, s
t_{ej}	time for ejection of die casting during part drop, s
t_{fc}	cavity fill time, s
t_{fs}	slow shot fill time, s
t_{lm}	manual ladling time, s
t_m	die casting machine cycle time, s
t_{oc}	time for die opening plus closing, s
t_p	trimming cycle time, s

t_{p0} trimming cycle time for a single-aperture trimming operation of the smallest part, s

Δt_p additional trimming cycle time for each aperture in multi-aperture trimming die, including loading time

T temperature at time t, °C

T_0 temperature at time t=0, °C

T_e recommended casting ejection temperature, °C

T_i adjusted melt injection temperature, °C

T_{ir} recommended melt injection temperature, °C

T_l liquidus temperature, °C

T_m initial average mold temperature, °C

T_{ms} mold surface temperature prior to shot, °C

T_r casting temperature ratio, dimensionless

T_s solidus temperature, °C

v_p plunger velocity, mm/s

V_c volume of cavities, mm^3

V_f volume of feed system, mm^3

V_o volume of overflow wells, mm^3

V_{sb} volume of sprue or biscuit, mm^3

V_s total shot volume, cc

W width of rectangular shot envelope, mm

w average wall thickness of the casting, mm

w_{ave} average wall thickness of die casting, mm

x position, mm

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CHAPTER 1: INTRODUCTION

1.1 Justification and Significance of the Work

The die casting cost estimation methodology presented in the following chapters is part of an ongoing research program at the University of Rhode Island, aimed at the development of a complete product design for manufacture system. It is now widely accepted that the improvement of manufacturing productivity is most effectively accomplished through the application of design for manufacture techniques in the early product design stage [1]. Manufacturing cost estimates have traditionally been done after detailed drawings and prototypes have been made. By this time, the manufacturing methods are fixed and it is too late to consider different processes that may significantly reduce costs [2]. In order to determine the most appropriate material/process combinations for components of a product, it is necessary, at the early design stage, to determine the relative costs of using various manufacturing processes.

The estimating procedures should require only information readily available to the designer at the early concept design stage such as knowledge of the basic geometric characteristics and the type of material. Since the estimates need to be performed by designers who may not have detailed knowledge of the manufacturing processes being considered, these estimates must be calculated by assuming optimum manufacturing conditions [3].

Die casting is an important process for consideration due to its ability to produce high strength components of very complex shapes [4]. This characteristic of the process allows the production of cast parts which can satisfy several functional requirements. This in turn allows designers the opportunity to reduce the total number of parts in the product, thereby minimizing assembly costs and increasing reliability [1].

1.2 Review of the Literature

A review of the literature indicates that the work done in die casting has been aimed mainly at determining the optimum processing conditions and at the design of feed or gating systems and die cavity forms to produce die cast parts with specified engineering requirements, such as mechanical strength properties [5,6,7,8,9]. Several cost estimation procedures have been developed [10,11], but these are intended for use after many parameters such as tooling costs and processing conditions have been determined or estimated by other means, usually by someone with considerable experience in the die casting industry. It is clear, therefore, that there is a need for a methodology for the early cost estimation of die cast parts.

1.3 Objectives and Limitations

The costs of the various elements of the die casting process are investigated in this thesis, in order to develop a manufacturing cost estimation methodology for die cast parts. The methodology will be used in the earliest product concept design stages in order to allow comparison with components produced by other competitive processes. The investigation is limited to pressure die casting, primarily of the engineering die casting alloys of aluminum and zinc.

In order to develop an early cost estimation procedure for die cast components, the cost is broken into several elements:

1. material cost
2. die casting die cost
3. trimming die cost
4. processing cost

In order to determine the die cost, a procedure for estimating the optimum number of cavities is developed. The processing cost is determined by developing an estimating procedure for the selection of appropriate machine size and an estimating procedure for determining the cycle time.

Development of such procedures requires considerable collection of industrial data in order to develop relationships between important cost parameters, as well as to approximate typical parameter values that describe optimum processing conditions. This will be evident in detailed discussions of such die casting parameters in the following chapters.

CHAPTER 2: DESCRIPTION OF THE DIE CASTING PROCESS

2.1 Brief Overview of the Die Casting Process

Summarizing the description given by Metals Handbook [12], the die casting process, also called pressure die casting, is a molding process in which a molten metal is injected under high pressure into cavities in reusable steel molds, called dies, and held under pressure during solidification. Very complex casting shapes can be produced due to the high injection pressures used.

The casting cycle consists of first closing and locking the die. The molten metal, which is maintained by a furnace at a specified temperature, then enters the injection cylinder. Depending on the type of alloy, either a hot-chamber or cold-chamber metal-pumping system is used. During the injection stage of the die casting, pressure is applied to the molten metal which is then driven quickly through the feed system of the die while air escapes from the die through vents. The volume of metal must be large enough to overflow the die cavities and fill overflow wells. These overflow wells are needed to maintain more constant die temperatures and reduce the amount of oxides. Once the cavities are filled, pressure on the metal is increased and held for a specified dwell time in which solidification takes place. The dies are then separated, and the part ejected, usually by means of automatic machine operation. The open dies are then cleaned and lubricated as needed and the casting cycle is repeated.

Following ejection, parts are often quenched and then trimmed to remove the runners which had been necessary for metal flow during mold filling. Trimming is also necessary to remove the overflow wells and any parting-line flash that is produced. Subsequently, secondary machining and surface finishing operations may be performed.

2.2 Machines

Die casting machines consist of several elements, namely: the die mounting and clamping system, the die, the metal pumping and injection system, the metal melting and storing system and any auxiliary equipment for mechanization of such operations as part extraction and die lubrication. Dies will be discussed in section 2.5 and auxiliary equipment will be discussed in section 2.8.

2.2.1 Die Mounting and Clamping Systems

The die casting machine must be able to open and close the die and lock it closed with enough force to overcome the pressure created by the molten metal in the cavity. The machines contain a moving platen which holds the ejector die half and a stationary platen which holds the cover or fixed die half. These platens are opened and closed by a mechanism that is powered pneumatically, mechanically, hydraulically, or by a combination of these. Compound mechanical toggles with the addition of hydraulic cylinder force are the most common type of closing mechanism [13].

The clamping systems are either solid cast frame machines or more commonly, four-bar tie-bar presses.

2.2.2 Metal Pumping and Injection Systems

The two basic types of injection systems are hot-chamber and cold-chamber. Hot-chamber systems, in which the pump is placed in the container of molten metal, are used with alloys of low melting temperatures, such as zinc. Cold-chamber machines must be used for high melting temperature alloys such as aluminum, copper-based alloys, and the ZA zinc alloys which contain large amounts of aluminum, because at high melting temperatures these alloys erode the ferrous injection pump components, thereby degrading the pump and contaminating the alloy. Magnesium alloys, although they are cast at high temperatures, can be cast in hot-chamber machines as well as cold-chamber machines because they are inert with respect to the ferrous machine components.[12]

2.2.2.1 Hot-Chamber Machines

A typical hot-chamber injection or shot system, as shown in Fig. 2.1, consists of two cylinders, a plunger, a gooseneck and a nozzle. The injection cycle begins with the

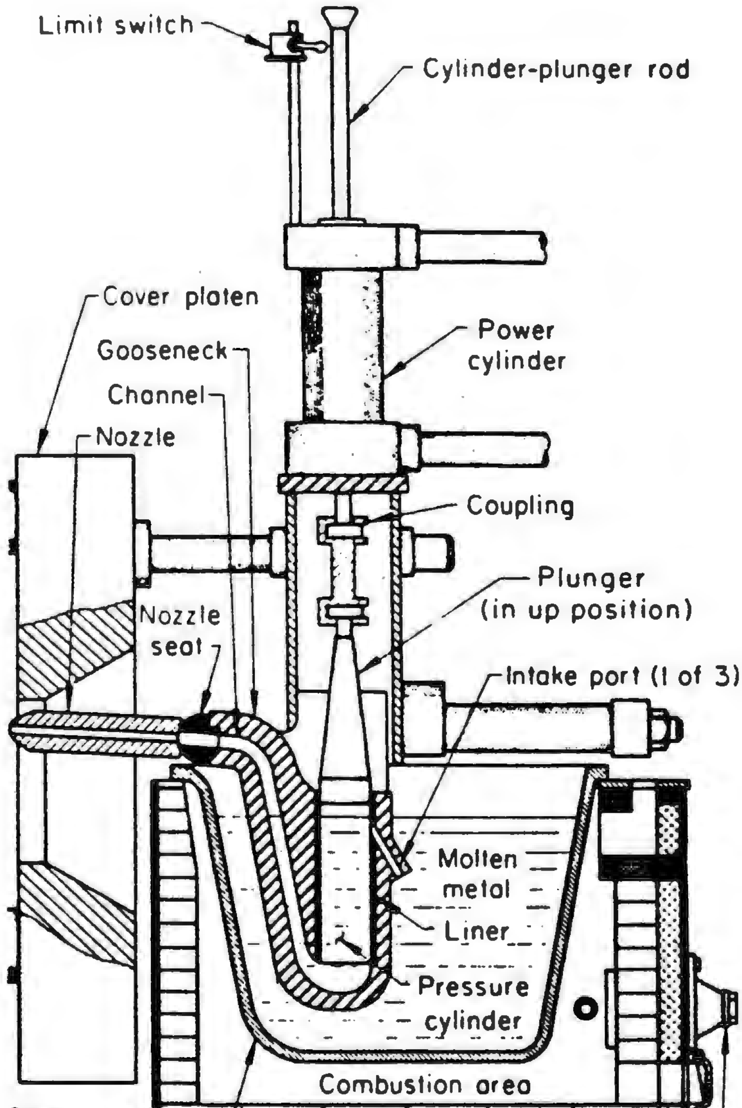

Figure 2.1: Typical Injection System of a Hot-Chamber Die Casting Machine (Reprinted from [12])

plunger in the up position. The molten metal flows from the metal-holding pot in the furnace, through the intake ports and into the pressure cylinder. Then with the dies closed and locked, the power cylinder moves the plunger down into the pressure cylinder and seals off the intake ports [12]. The power cylinder is driven by a hydraulic accumulator. A hydraulic pump supplies the oil to the accumulator at a rate that brings its pressure up to operating level for each shot [14].

The molten metal is forced through the gooseneck channel and the nozzle and into the die cavity. The power cylinder is then activated in the reverse direction after a preset dwell time for metal solidification, and the plunger is pulled up. The cycle then repeats. Cycle times range from several seconds for castings weighing less than one ounce to thirty seconds for castings weighing several pounds [15].

2.2.2.2 Horizontal Cold-Chamber Machines

A typical cold-chamber machine, as shown in Figs. 2.2 and 2.3, consists of a horizontal shot chamber with a pouring hole on the top, a water cooled plunger, and a pressurized injection cylinder. The sequence of operations, illustrated in Fig. 2.4 is as follows [12]: while the die is closed and locked, and the cylinder plunger is retracted, the molten metal is ladled into the shot chamber through the pouring hole. In order to tightly pack the metal in the cavity, the volume of metal poured into the chamber is

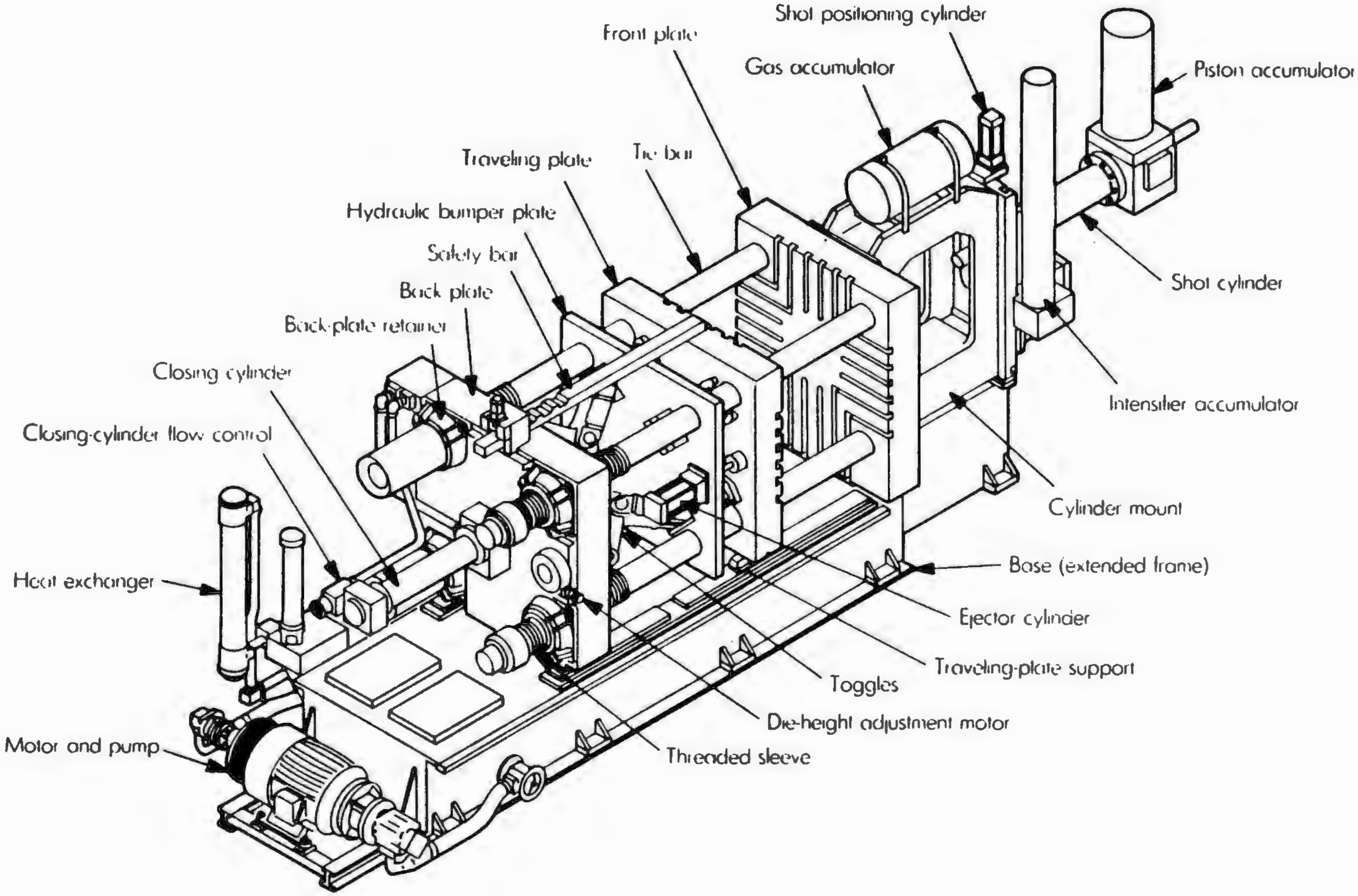

Figure 2.2: General Layout of a Typical Cold-Chamber Die Casting Machine (Reprinted from [13])

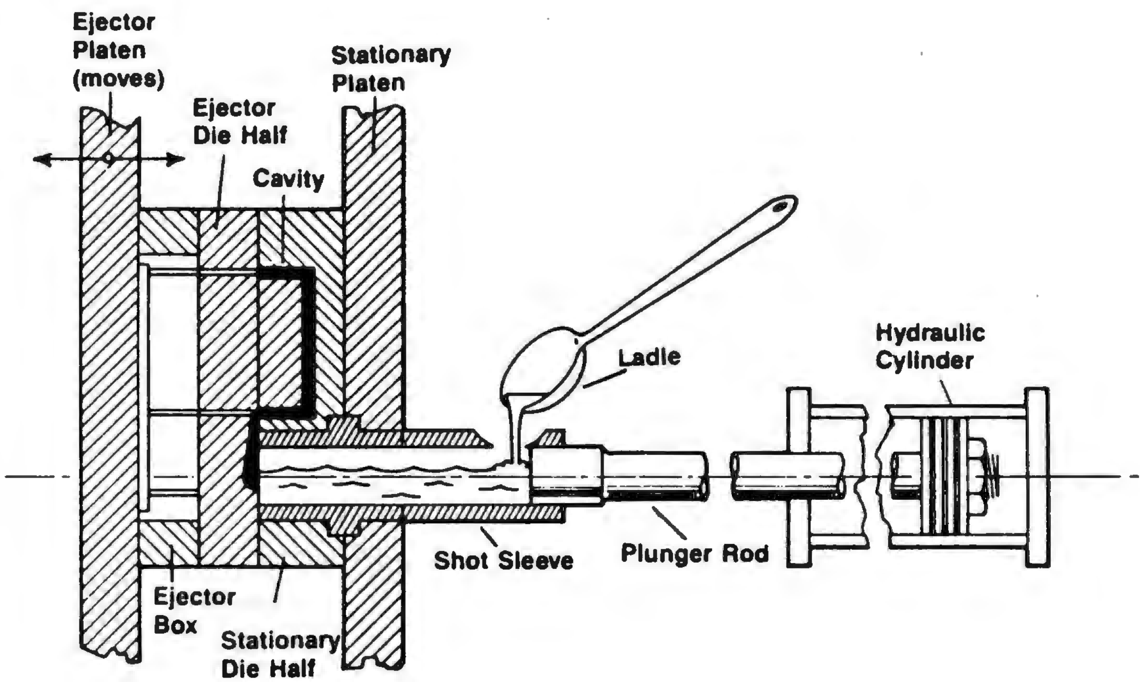

Figure 2.3: Die, Shot Chamber, and Plunger of a Cold-Chamber Machine (Reprinted from [15])

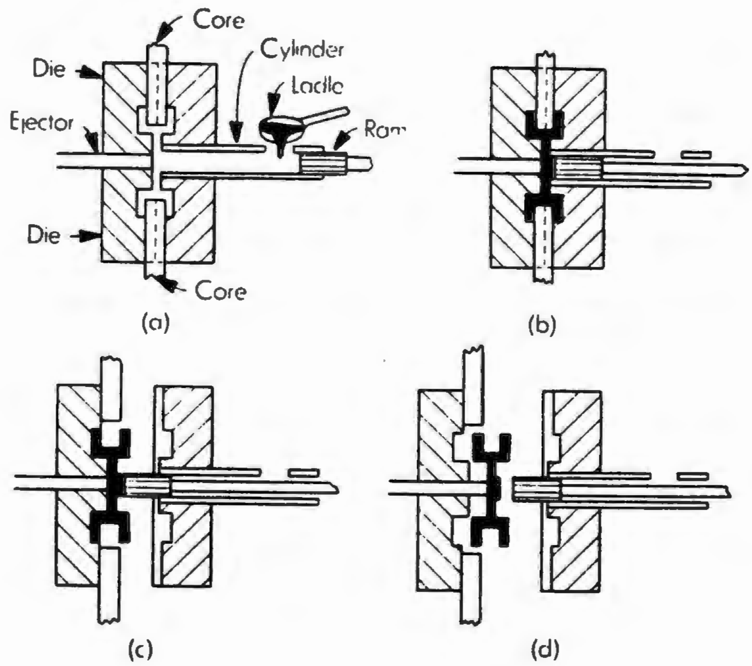

Figure 2.4: Cold-Chamber Die Casting Machine Sequence of Operations: (a) Cylinder is Filled with Molten Metal; (b) Ram Forces Metal into Die; (c) Die is Opened; (d) Casting is Ejected (Reprinted from [13])

greater than the combined volume of the cavity, the feed system, and the overflow wells. The injection cylinder is then energized, moving the plunger through the chamber, thereby forcing the molten metal into the die cavity. After the metal has solidified, the die opens and the plunger moves back to its original position. As the die opens, the excess metal at the end of the injection cylinder, called the biscuit, is forced out of the cylinder because it is attached to the casting. The action of the plunger pushing on the biscuit also separates the casting from the cover die. The machine is then ready for the next cycle.

2.2.2.3 Vertical Cold-Chamber Machines

Vertical cold-chamber machines, used to cast some aluminum specialty alloys, as well as some traditional aluminum alloys, and used for producing radially symmetrical castings and castings that require minimum porosity [13], have either vertical die parting (Fig. 2.5), or, more commonly, horizontal die parting (Fig. 2.6). With the latter, the metal is drawn from below the vertical shot chamber by evacuation of the air from the die. When the plunger is activated, the molten metal is forced up into the cavity. Die clamping pressures and injection pressures are controlled by a single actuator, thus eliminating the chance of unbalanced pressure.

In injection systems of vertical cold-chamber machines with vertically parting dies, the metal is ladled into the

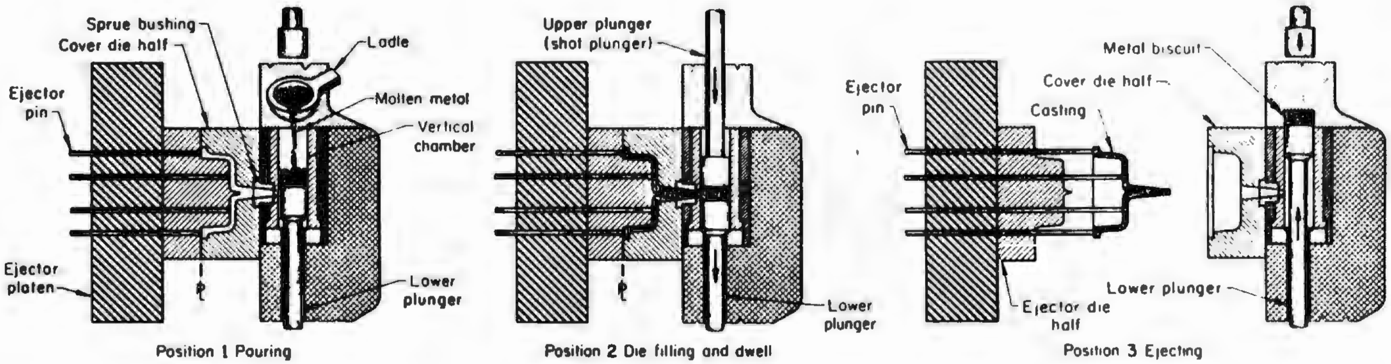

Figure 2.5: Operating Cycle of a Vertical Cold-Chamber Die Casting Machine with Vertical Die Parting (Reprinted from [12])

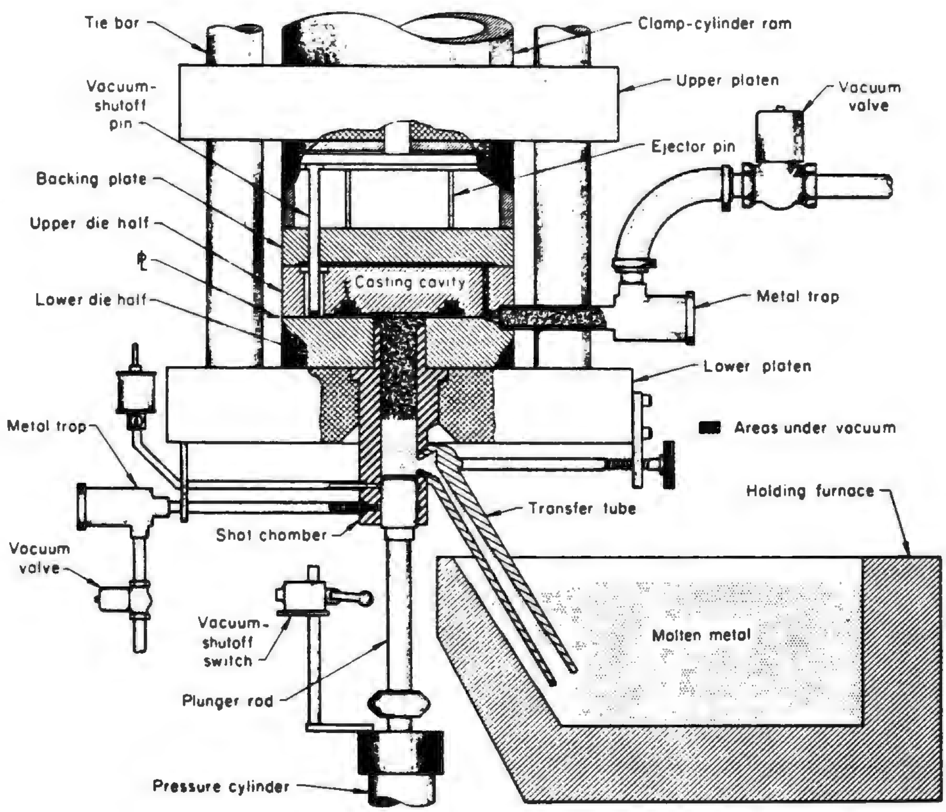

Figure 2.6: Vertical Cold-Chamber Die Casting Machine with the Die Parting-Line in the Horizontal Plane (Reprinted from [12])

top of the vertical shot chamber, that is connected directly to the cover die half, while the lower plunger is then actuated, forcing the lower plunger down, thereby allowing the metal to flow through the sprue bushing and into the die. After the dwell cycle, the upper plunger is retracted while the lower plunger rises and shears the biscuit from the sprue and ejects it.

2.3 Alloys

The four major types of alloys that are die cast are zinc, aluminum, magnesium, and copper-based alloys. Lead and tin are less frequently die cast due to their poor mechanical properties, and will not be considered in this report. Tables of the physical, mechanical, and processing properties of these alloys are listed in the Appendix.

The most common die casting alloys are the aluminum alloys [15]. They have low density, have good corrosion resistance, are relatively easy to cast, and have good mechanical properties and dimensional stability. Aluminum alloys have the disadvantage of requiring the use of cold chamber machines which usually have longer cycle times than hot chamber machines due to the need for a separate ladling operation.

Zinc-based alloys are the easiest to cast. They also have high ductility and good impact strength, and therefore can be used for a wide range of products. Castings can be made with very thin walls, as well as excellent surface smoothness, leading to ease of preparation for plating and painting. Zinc alloy castings, however, must usually be coated using one of the processes described in section 2.7, adding significantly to the total cost of the component.

Zinc-Aluminum (ZA) alloys are composed of a higher aluminum content (8 - 27%) than the standard zinc alloys. Thin walls and long die lives can be obtained, similar to standard zinc alloys, but, as with aluminum alloys, cold chamber machines must be used.

Magnesium alloys have very low density, have a high strength-to-weight ratio, exceptional damping capacity, and have excellent machinability. These castings cannot be polished because the surface quickly oxidizes and they usually require coating.

Copper-based alloys, brass and bronze, provide the highest mechanical properties of any of the die casting alloys, but are much more expensive. Brasses have high strength and toughness, good wear resistance and excellent corrosion resistance. One disadvantage of copper-based alloy casting is the high die cost due to short die life caused by thermal fatigue of the dies at the extremely high temperatures necessary for casting these alloys.

2.4 Metal Handling

2.4.1 Metal Melting and Storing Systems

The die casting process requires the use of furnaces for the melting of metal ingots, for remelting of scrap, and for holding the molten metal at the proper temperature near the die casting machine.

2.4.2 Metal Transfer and Feeding

Metal transfer often involves two basic operations, transferring the molten metal from the melting furnace to the holding furnace and then transferring the metal from the holding furnace to the shot chamber of the die casting machine. In small production facilities, however, ingots are often melted directly in the holding furnaces of individual hot chamber machines.

Melting and holding are usually separate operations. A large melting furnace usually supplies the molten metal to several smaller holding furnaces located at the die casting machines.

Metal is transferred to the holding furnaces by one of the following: ceramic pumps, large transfer ladles, or hand ladles.

Metal is transferred to the shot chamber by either: manual or mechanized ladling, pressure systems (including pressure on the surface of the metal, vacuum ahead of the metal, or gravity), or positive displacement or positive pressure pumps.

Hand ladling, sometimes used for cold chamber operations, has low initial and maintenance costs. But, metal contamination is more likely because the metal is ladled from the top of the pot where more oxides form. Also, the ladling rate may be inconsistent because it is done by a manual operator who is subject to fatigue.

Mechanized ladles, operated by air cylinders can be synchronized with the machine cycle. Also, cleaner metal is ladled because the metal can be taken from below the surface of the bath.

The method of using pressure on the top surface of the bath is used for the die casting of aluminum alloys. The metal is forced out of an orifice near the bottom of the pot and up a spout, similar to a teapot, and into the shot chamber as shown in Fig. 2.7. This enables the use of metal that is more pure. Shots weighing up to 45 kg(100 lb) can be made [12].

Vacuum-feed systems create a vacuum in the die cavity (Fig. 2.8) or shot sleeve (Fig. 2.9) and draw the molten metal directly from the holding pot, through a heated tube into the shot chamber. After a preset interval the plunger moves forward to seal off the flow of metal in the chamber and to force the metal from the shot chamber into the die cavity. Vacuum-feed systems have shorter cycle times due to

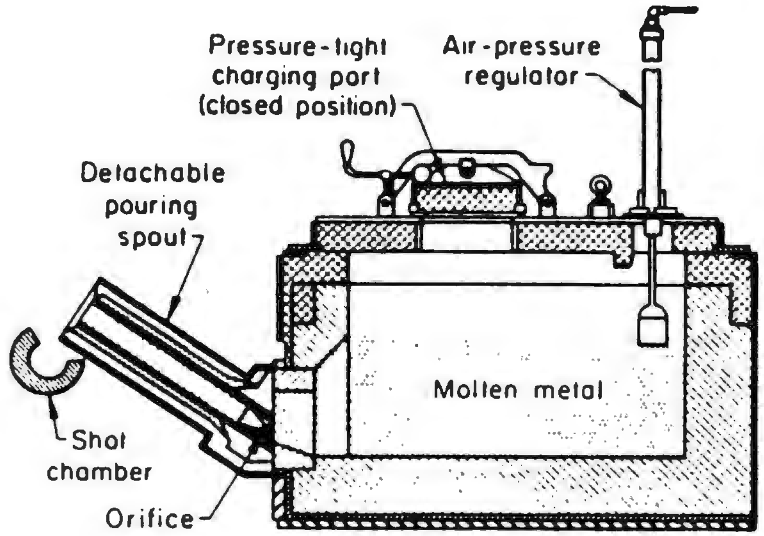

Figure 2.7: Air-Pressure System For Supplying Clean Molten Metal to the Shot Chamber of a Cold-Chamber Die Casting Machine (Reprinted from [12])

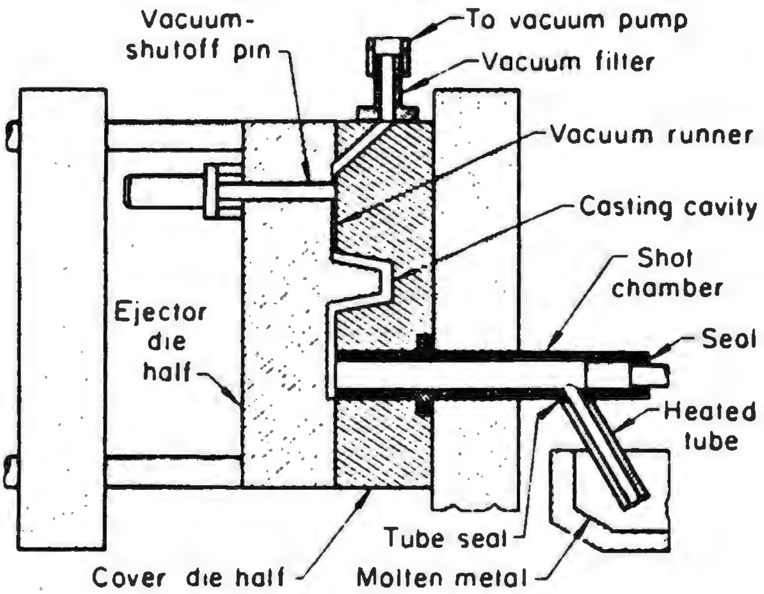

Figure 2.8: Vacuum-Feed System for Supplying Molten Metal to the Shot Chamber of a Cold-Chamber Die Casting Machine (Reprinted from [12])

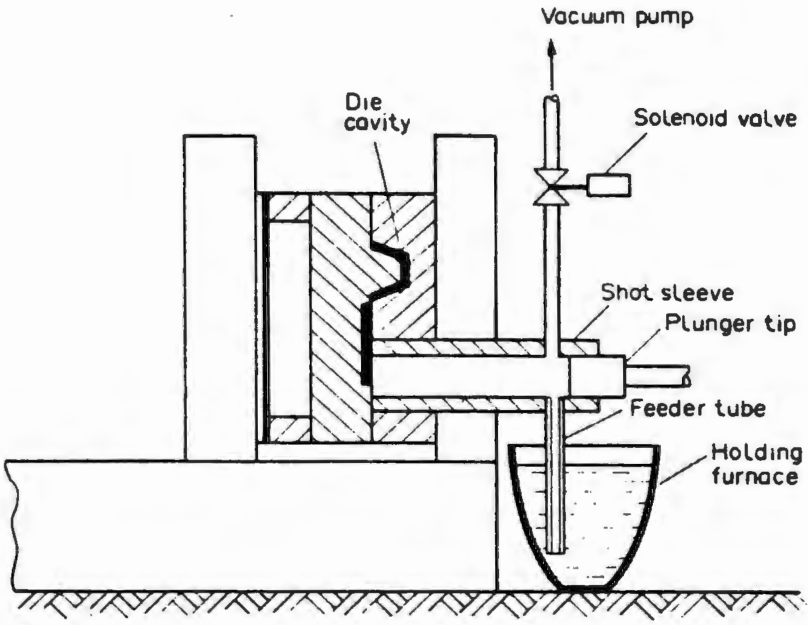

Figure 2.9: Vacuum-Type Transfer System with the Vacuum Cut-Off in the Shot Sleeve (Reprinted from [7])

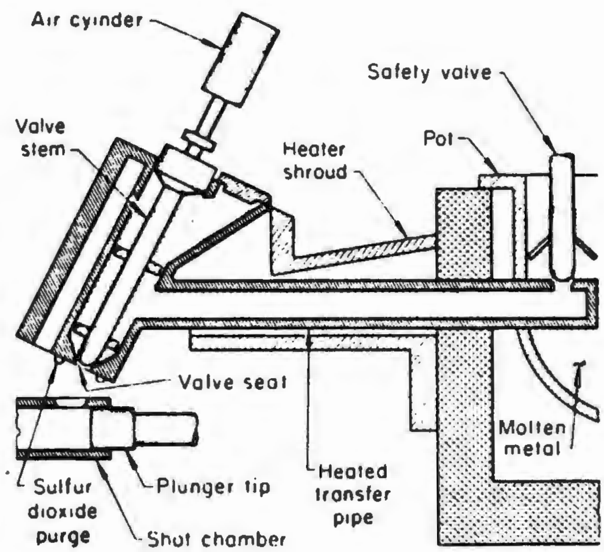

Figure 2.10: Gravity-Feed System for Supplying Molten Magnesium Alloy to the Shot Chamber of a Cold-Chamber Die Casting Machine (Reprinted from [12])

the speed of metal delivery. Vacuum-feed systems can be used with any type of alloy.

Gravity systems (Fig. 2.10), although not used extensively, can be used for magnesium die casting. The molten metal is allowed to fill a heated transfer pipe at a level lower than the top of the melt in the pot. An air cylinder activated valve is opened at predetermined intervals allowing the metal to flow down into the top of the shot chamber.

Pumps are used to feed magnesium and less commonly, aluminum alloys. The centrifugal pump impeller is incased and submerged in the holding pot (Fig. 2.11). At preset time intervals, the pump goes from low speed to high speed while a valve is opened to allow the metal to flow up through a delivery tube and into the shot chamber.

2.5 Dies

Die casting dies (Figs. 2.12 and 2.13) consist of two major sections - the ejector die half and the cover die half - that meet at the parting-line. The cavities and cores are usually machined into inserts that are fitted into each of these halves. The cover die half is secured to the stationary platen, while the ejector die half is fastened to the movable platen. The cavity and matching core must be designed such that the die halves can be pulled away from the solidified casting. In other words, undercuts must be avoided. The majority of the cavity volume is usually

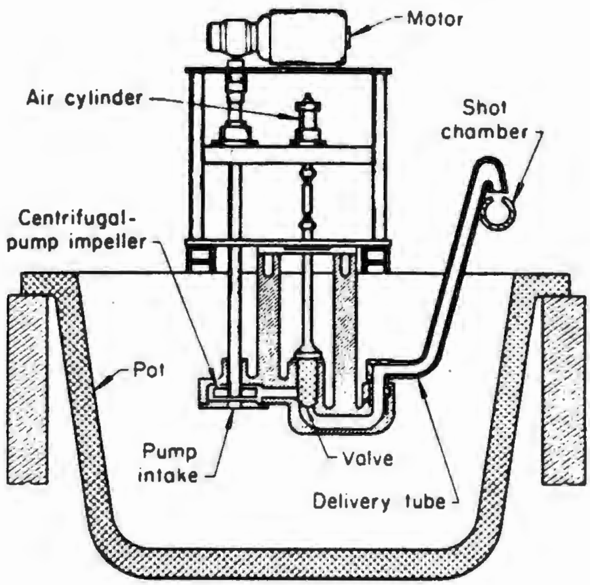

Figure 2.11: Constant-Pressure Centrifugal Pump for Feeding Molten Magnesium Alloy to the Shot Chamber of a Cold-Chamber Die Casting Machine (Reprinted from [12])

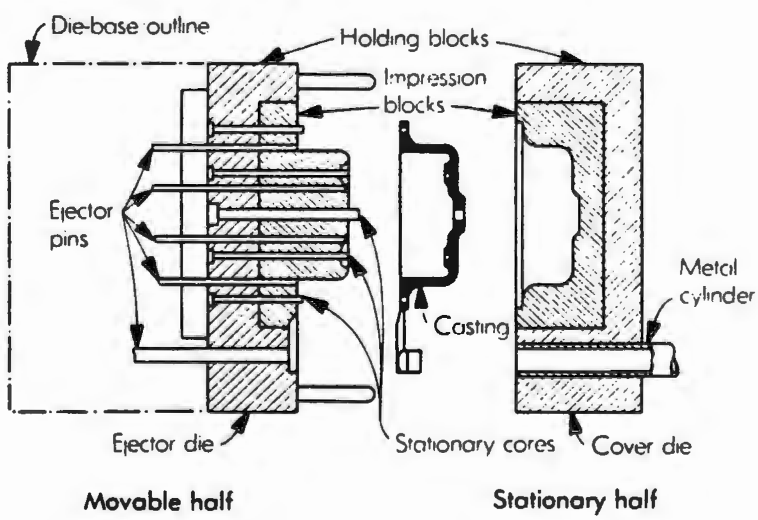

Figure 2.12: Typical Die Casting Die (Reprinted from [13])

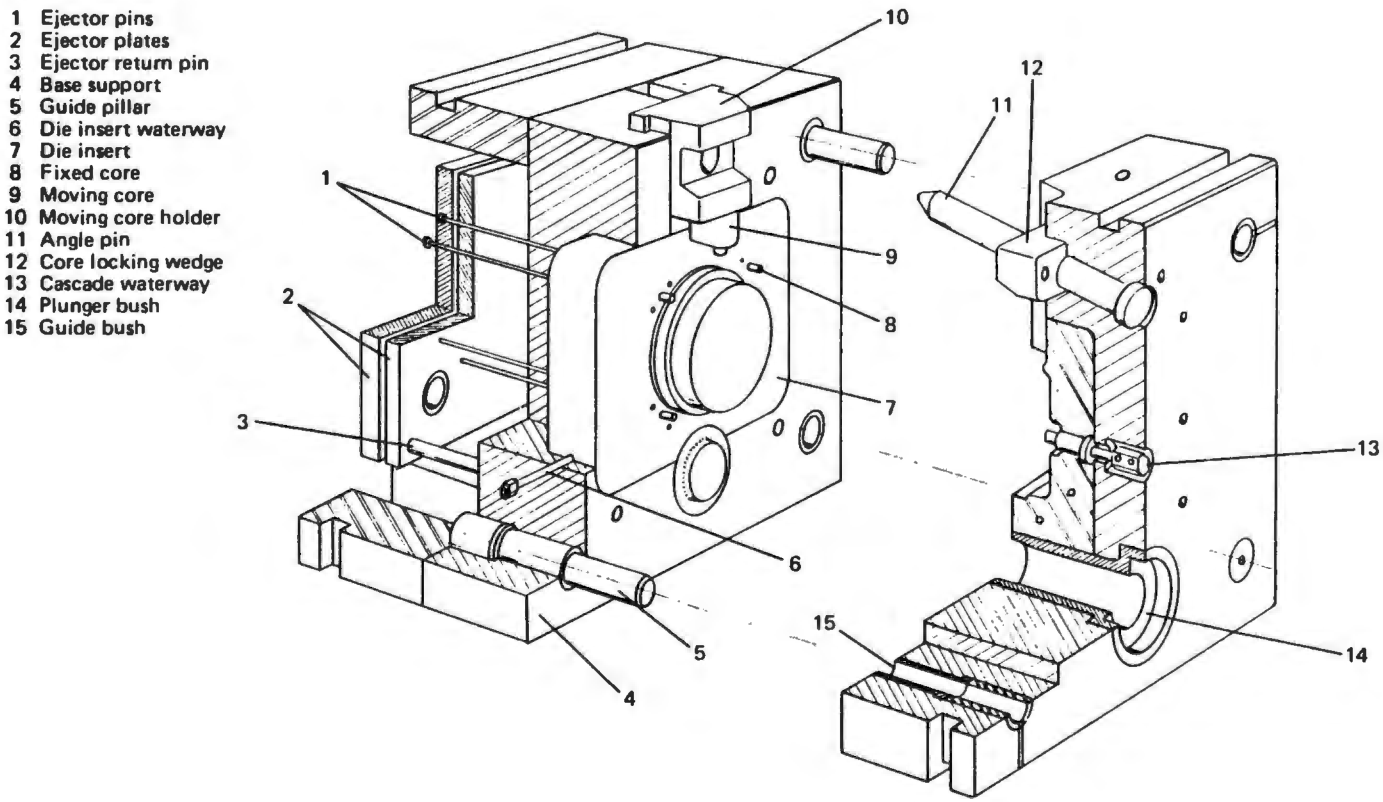

Figure 2.13: Typical Die Assembly (Reprinted from [16])

machined into the cover die half while the mating half is machined into the ejector die half. For example, if a cup shape is desired, the inside contour would exist on the ejector die half. This is done so that when the casting cools it will shrink and remain on the core of the protruding ejector die half when the dies are opened. The casting is then removed by an ejector system built into the ejector die half. This system consists of pins that protrude into the cavity during die opening, and a mechanism for this pin movement, such as that shown in the hot chamber die in Fig. 2.14. The placement and number of pins used is such that the marks left are not objectionable and that the part is ejected without distortion [12].

In addition to the shape of the cavity, other features, such as runners, gates, vents, and overflow wells must be machined into each die, usually in the cover die half. First, a sprue or shot hole is machined to align with the injector nozzle (hot-chamber) or shot chamber (cold-chamber) in the injection system. In the hot-chamber process, a sprue spreader is often added to the ejector die half. The metal is directed to various sections of the cavity by runners. The runners terminate at gates of smaller cross-sectional area, designed to increase metal flow velocity upon entering the cavity thereby reducing turbulence of the molten metal. Overflow wells are usually designed into the cavity for several reasons: to maintain a more constant die temperature on small castings, by adding a substantially to

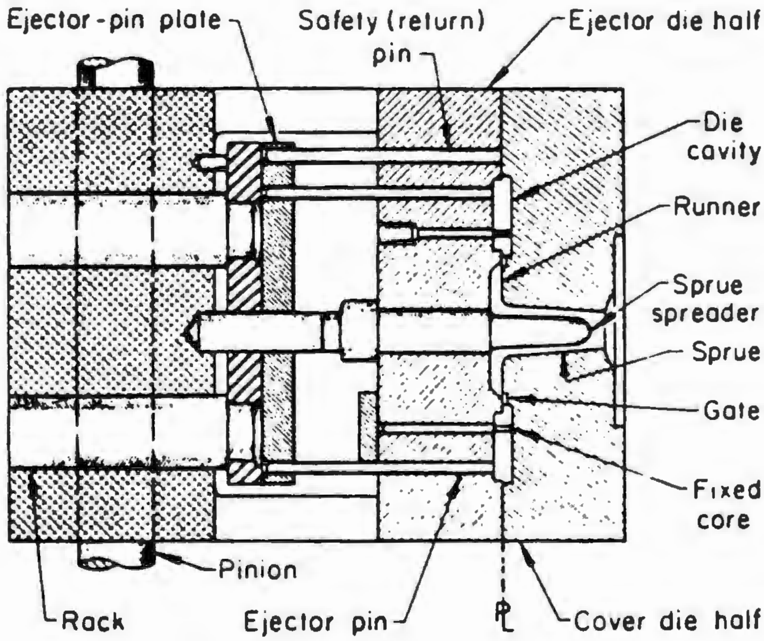

Figure 2.14: Principal Components of a Simple Hot-Chamber Die Casting Die with Integral Rack-and-Pinion Ejection (Reprinted from [12])

the mass of molten metal, and to reduce the amount of oxides in the casting, by allowing the cooler, first part of the shot to move through the cavity and force the air into the vents. This initial portion of the shot reacts with the air in the cavity to form oxides which are then carried out of the cavity and into the overflow wells. These overflow wells are later trimmed off and remelted. The remaining portion of the shot and the die are at a higher temperature thereby reducing the chance of the metal freezing prematurely, leading to the formation of surface defects called cold shuts, in which streams of metal do not weld together properly because they have partially solidified by the time they meet. Vents are necessary for evacuation of the air present in the die prior to injection of the molten metal.

Cores are die components used to produce holes and other casting features. Fixed cores move parallel to the die movement. However, if side holes, undercuts, or side depressions exist then movable or side cores must be removed from the solidified casting before the casting is ejected. This is accomplished by cam pins or by hydraulic cylinders which are locked in place when the die is closed.

Another feature of die casting dies is die cooling. Water-cooling channels, called cooling lines or water lines, are placed in the die, as seen in Fig. 2.15, to control the die temperature and to dissipate heat around the sprue and other heavy cross-sections of the casting.

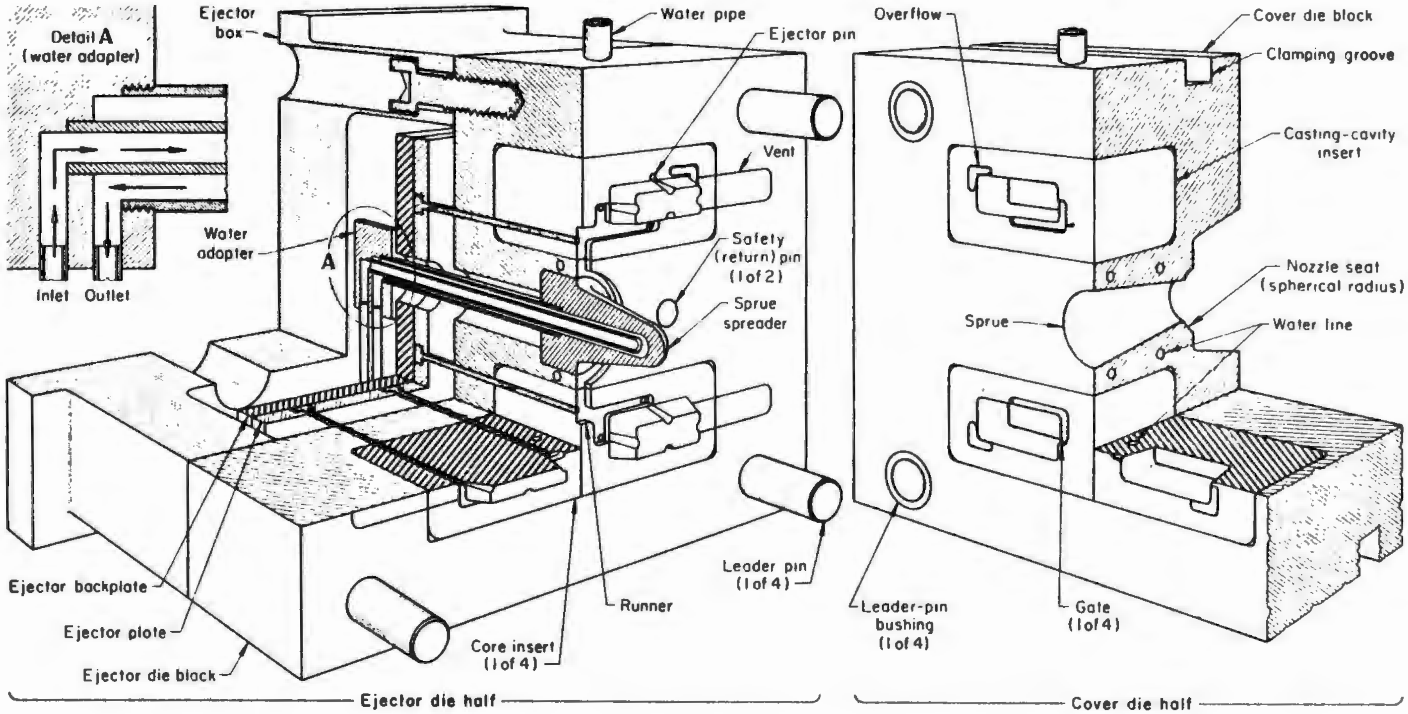

Figure 2.15: Multiple-Cavity Die for Casting Four Automotive Lamp Bezels per Shot (Reprinted from [12])

Sometimes dies are also heated near thin sections of the casting to prevent freezing off before the cavity has filled. Dies are also sometimes preheated.[14]

Several types of dies are available as shown in Fig. 2.16. Dies can be made as single-cavity dies or multiple-cavity dies, depending on the size of the casting, the type of machine being used, the production volume, and the complexity of the casting (i.e. the number of side cores and slides necessary, as each of these requires mechanisms for removal from the die). The use of multiple-cavity dies consisting of several identical cavities can significantly reduce the cost of die castings for large production volumes.

Combination or "family" dies consisting of several cavities, each for casting a different component of a single final assembly, are also used. Another option is the use of unit dies which are usually single-cavity dies that are inserted into a master die. The master die holds several replaceable, interchangeable, unit dies.

Die casting dies must be lubricated to prevent the casting from adhering to the die, to permit a better surface finish, and to allow the molten metal to flow into smaller cavities. Other moving parts of the die and machine, such as ejectors, cores, slides, plungers and rams, and shot chambers, must also be lubricated.

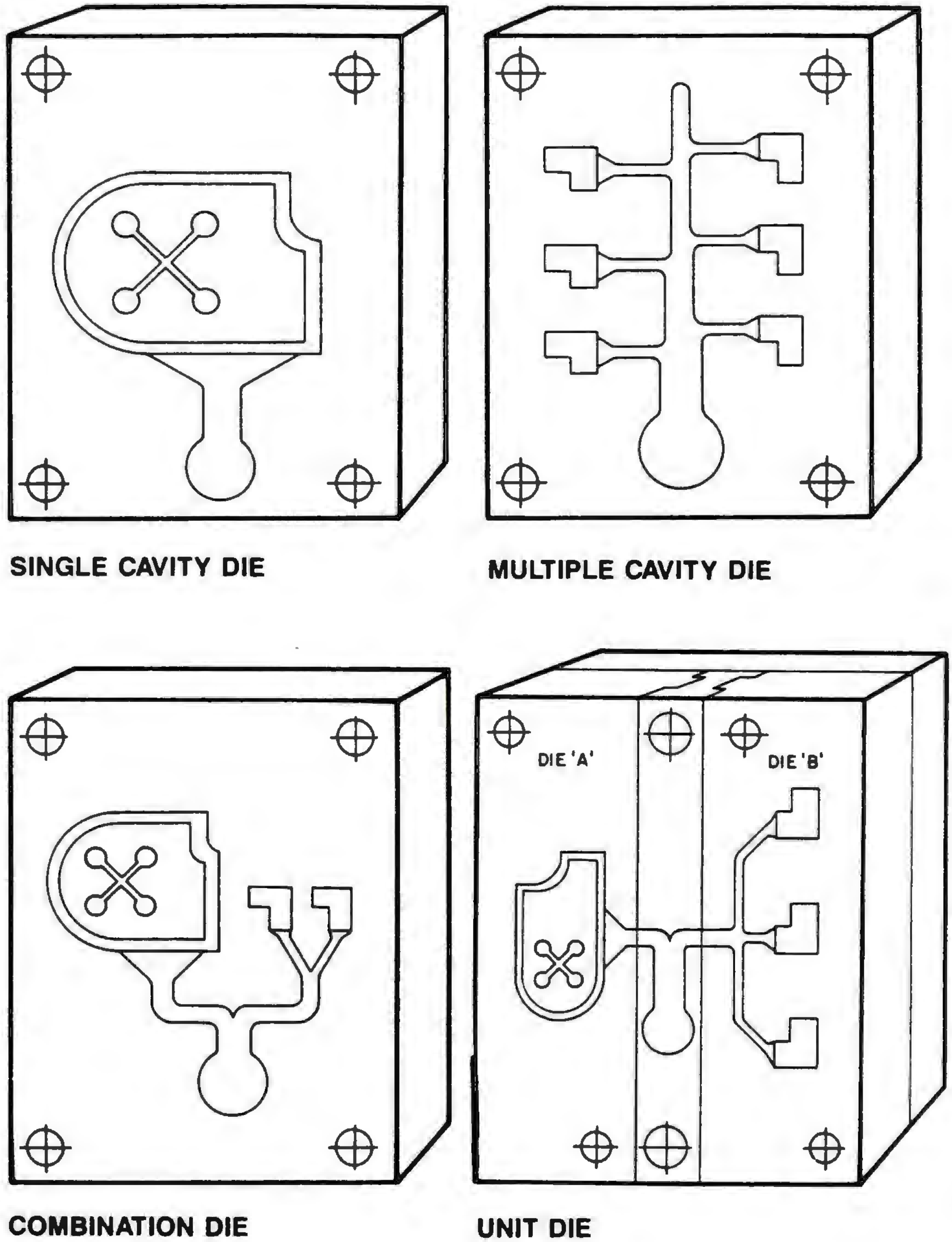

Figure 2.16: Types of Dies (Reprinted from [15])

2.6 Trimming

Upon extraction from the die casting machines, runners, gates, overflow and parting-line flash must be removed from the casting. This is done either manually or, if production quantities are large, with trimming presses. Trimming presses are similar to blanking and piercing dies used for sheet metal pressworking. They are mounted on mechanical or hydraulic presses, and because the required forces are low, the bed area to tonnage rating ratio is relatively large. The thickness of the metal to be trimmed is usually 0.75-1.3mm (0.030-0.050 in). Depending on the production volume, trimming dies range from simple punches to complex dies with side slides to permit trimming of complex castings, in more than one direction [12,7].

Among the manual methods used are removal of thick gates on aluminum and brass castings by a band-saw, or simply removing runners and gates by hand or with a hammer.

It is desirable, when designing a casting, to locate the main gates and overflow gates at the parting line of the casting and to design a parting line that is not stepped. This simplifies both the casting die and the trimming die. In addition, gates should be designed as thin as possible for ease of removal.

2.7 Finishing

Following trimming, castings are often polished and then coated to provide corrosion resistance, wear resistance, and to improve aesthetic appearance. Polishing operations may include grinding along the parting-line to remove flash and gate residue left by the trimming operation. Spot polishing with a finer abrasive is then performed in order to remove burrs or defects, or all-over polishing is performed. Barrel finishing may also be used for zinc and brass castings because the higher density and toughness of these materials assists in the polishing action [7].

Once the casting is sufficiently polished, it may be prepared for coating or in the case of many aluminum parts it may be ready for use. Before coating, parts are put through a series of cleaning operations that remove any contamination that could prevent the adhesion of these applied coatings. The cleaning operations usually performed are degreasing, alkaline cleaning, and acid dipping.

Following cleaning, several coatings are available depending on the type of alloy cast. These coatings may be separated into three groups, namely: electroplating, anodizing, and painting. Electroplating, is used mainly for zinc alloy castings because aluminum, and magnesium alloys oxidize quickly preventing the electroplate layers from adhering properly, and brass castings, although they may be electroplated after removal of oxides, are often used unfinished.

The most common type of electroplating is a decorative chrome finish on zinc die castings, which consists of several layers of applied metal. First, a very thin layer of copper (0.008 mm), is applied to aid in the adhesion of the subsequent layers. A second layer of copper is then sometimes added to improve the final surface finish. Two layers of nickel, 0.025 mm thick, are then applied. These layers aid in corrosion resistance by diverting the corrosion to the outer layer of nickel because of the difference in electrical potential between the two layers. The final layer is a thin coat of chromium (0.003 mm), which also helps to prevent corrosion by serving as a barrier [16].

Anodizing, used on aluminum, zinc, and magnesium alloy castings, provides corrosion resistance, wear resistance, and may also serve as a base for painting. Anodizing of aluminum is the formation of a layer, 0.005-0.030 mm thick, of stable oxides on the surface of the base metal by making the casting the anode in an electrolytic cell, with separate cathodes of lead, aluminum or stainless steel. This surface is usually a dull grey and therefore not usually applied for decorative purposes.

The process of anodizing zinc, is quite different in that an oxide coating is not formed. Instead, a layer of semi-fused composite of oxides, phosphates, and chromates is produced by a high voltage anodic spark discharge. The coating produced is moss green and approximately 0.031 mm thick [17]. The coating is corrosion resistant and non-conductive, as well as an excellent base for paints and lacquers.

In the case of magnesium castings, a thickened layer of the naturally occurring protection is similarly applied, but by the process of chemical conversion. A complex reduction-oxidation reaction occurs in which the magnesium is oxidized and conversion salt is reduced.

The most common form of applied coating for aesthetic appearance and protection is painting. Paint may be applied to bare metal, primed metal, or to surfaces that have additional protective coatings. Paint is often applied by electrostatic painting or by electropainting. Electrostatic painting involves applying a high electrical potential to the casting and then using powdered paint sprayed through a nozzle of the opposite electrical potential. In electropainting, the casting is made cathodic relative to the steel tank that contains the water-soluble, resin-based paint. This process enables one thick coat of paint to replace two thinner coats.

Zinc castings can also be coated by vacuum metallizing, in which a thin metallic film is applied onto a lacquered surface with a high vacuum. This process can produce the appearance of copper, silver, brass, and gold. Plastic coating is another process available for zinc die castings.

Usually, the castings are first chromate treated and then sprayed with an epoxy powder coating. The parts are then cured. One advantage of plastic coating over liquid painting is that it is easy to change powder reservoirs and therefore small batches of different colors can be produced.

Brass castings are usually used unfinished, but may be polished and lacquered.

The process of impregnation, while not a surface finishing process, is performed after the casting and polishing processes have been completed. Impregnation is used on castings where porosity may produce structural problems, as in the case were castings are to be used to hold fluids or to contain fluid pressure. Impregnation may also be performed before plating operations because plating solutions that are trapped in pores may cause surface blemishes. Porosity tends to be a problem when the casting has been machined through the surface skin to expose the porous center, or in thick sections of the casting which contain more porosity. The process of impregnation consists of placing the castings in a vacuum chamber, evacuating the pores, and immersing the castings in a sealant. The sealant is then forced into the pores once the casting is in atmospheric pressure. Three types of sealants used are sodium silicate, polyester resin, and anaerobic sealants. The castings are often cured after impregnation.

2.8 Auxiliary Equipment for Mechanization

Several operations in die casting are sometimes mechanized in order to reduce cycle times and to produce more consistent quality. Some of these operations utilizing mechanized equipment are the removal of the casting from the die, transfer of castings to subsequent operations, trimming, application of die lubricants, and transfer of molten metal to the shot chamber of cold chamber machines [12,7].

There are two main types of automatic systems for removing castings from the die, namely: secondary ejection and extraction. Secondary ejection systems, used mainly on hot chamber machines, involve dislodging the casting from the ends of the ejector pins following ejection of the casting from the cavity. The casting then falls from the die onto a conveyor located at the bottom of a quench tank filled with water. This process is usually only suited for small and fairly simple die castings that are easily dislodged and that are not damaged by the fall.

Extraction involves the use of a mechanical clamping device that simulates the actions of a human operator. The fingers of the clamp are open upon entry into the die opening, they then close on the casting, pull it out of the die, and drop it onto a conveyor belt or into a trim die. These devices range from simple mechanisms that move in only one plane, to programmable robots that are capable of movement in several planes.

Trimming of the casting may be automated by a procedure called in-the-die trimming (Fig. 2.17) that uses a complex die incorporating a casting cavity, a trimming die, and an indexing hub. After the casting solidifies, the die opens and the indexing hub rotates so the casting moves from the die cavity to the trimming section of the die. When the die closes, the part is trimmed, while the next casting is produced. This shortens the cycle time by eliminating the component of the trimming time.

Die lubricants may be applied automatically by stationary spray heads located near the die, or by reciprocating spray heads that enter the die after the casting has been extracted. These are sometimes mounted to the back of the extractor arm and are sprayed as the arm is retracting from the die.

Automatic metal transfer systems are used to transfer molten metal from the holding furnace to the shot chamber of cold chamber die casting machines. These systems may be mechanical ladles, pneumatic dispensing units, or electromagnetic pumps. Mechanical ladles may be of the dipping ladle type shown in Fig. 2.18 , the linear slide type, Fig. 2.19 , or a pivoting arm type. Bottom filling ladles (Fig. 2.20) are also used, as they reduce the amount of oxide picked up. Pneumatic dispensing units are either vacuum systems or low-pressure systems, described previously in section 2.4.2.

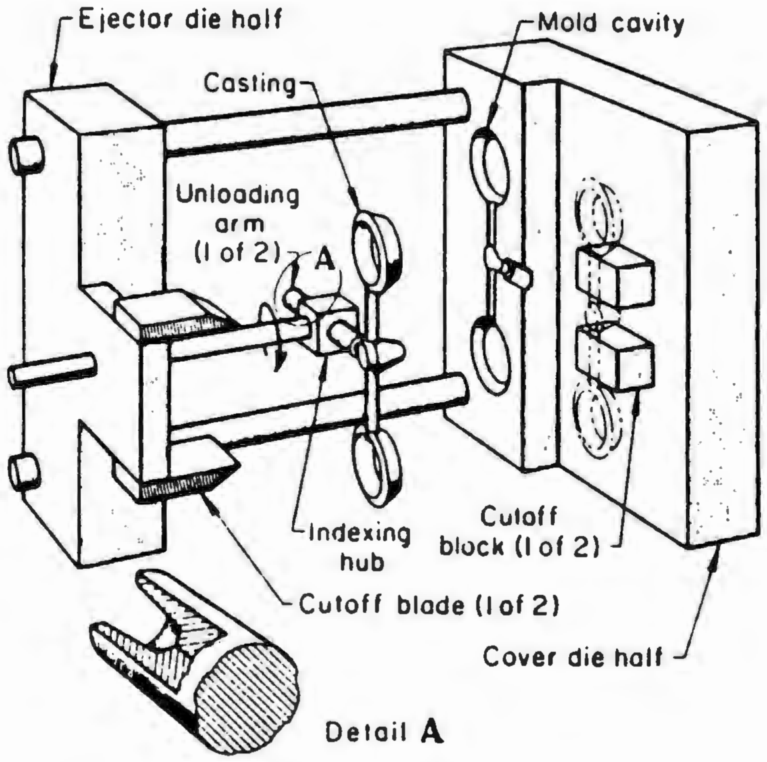

Figure 2.17: Die Equipped for In-the-Die Trimming (Reprinted from [12])

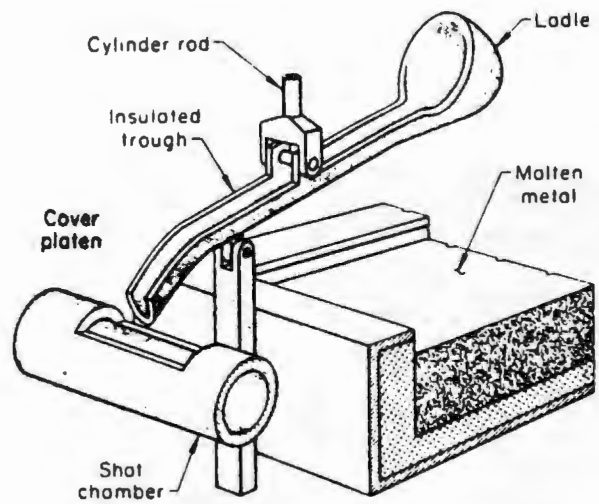

Figure 2.18: Dipping Ladle (Reprinted from [12])

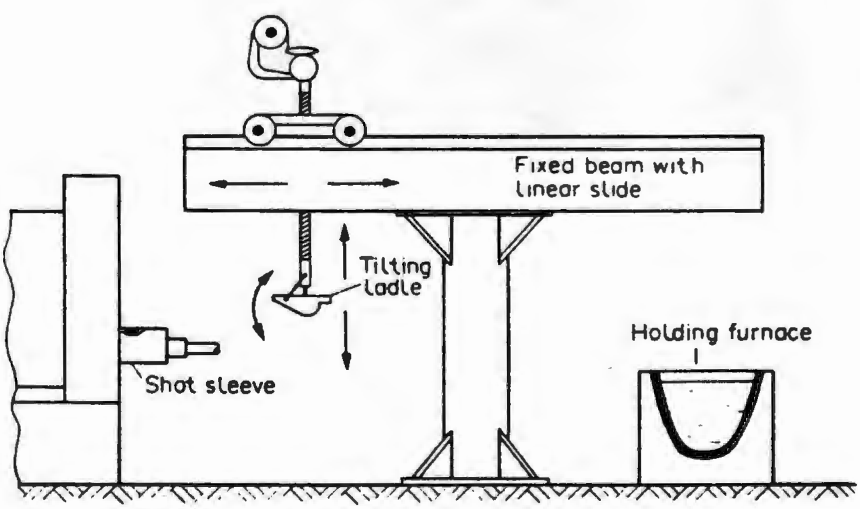

Figure 2.19: Linear Slide Type Transfer Ladle (Reprinted from [7])

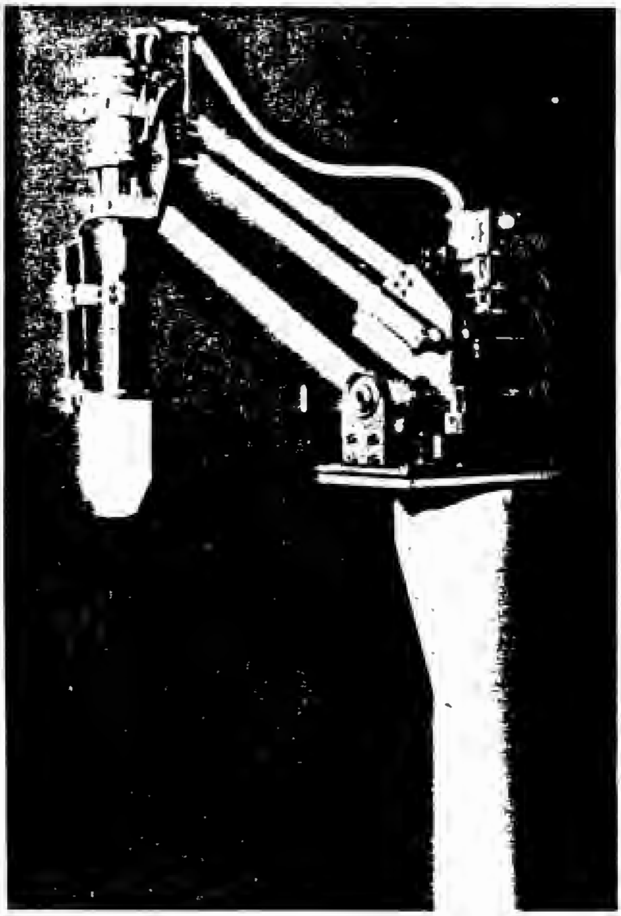

Figure 2.20: Bottom Filling Ladle (Reprinted from [7])

CHAPTER 3: DIE CASTING PROCESSING COST

The die casting processing cost is the product of the die casting cycle time and the operating rate of the die casting machine and its operator. In order to determine the operating rate, the machine size must be known. This in turn can only be determined if the number of die cavities is known. Since the procedures being developed in this work are to be used in early design, the number of cavities which may be used in later manufacturing cannot be ascertained with certainty. It can only be assumed that the part will be manufactured in an efficient manner. Thus, a value for what is likely to be an optimum number of cavities must be used. The determination of this value is the subject of the next section.

3.1 Determination of Optimum Number of Cavities

The optimum number of die cavities to be used in the die casting die, equal to the number of apertures in the trim die, can be determined for a particular die casting task by first calculating the most economical number of cavities, and then analyzing the physical constraints of the equipment to ensure that the economical number of cavities is practical. The most economical number of cavities can be determined by examination of the following equation for the total cost (not including the cost of secondary operations such as coating) of NT die castings which are to be produced:

$$CT = CDC + CTR + C_{dn} + C_{tn} + CA \ , \tag{3.1}$$

where: CT = total cost, \$,

CDC = die casting processing cost, \$,

CTR = trimming processing cost, \$,

C_{dn} = multi-cavity die casting die cost, \$,

C_{tn} = multi-aperture trim die cost, \$, and

CA = total alloy cost, \$.

The die casting processing cost, CDC, is the cost of operating the appropriate size die casting machine, and can be represented by the following equation:

$$CDC = \frac{NT}{n_c} C_{rd} * t_m * \frac{1 \text{ hr}}{3600 \text{ s}} \ , \tag{3.2}$$

where: NT = total number of components to be cast,

n_c = number of cavities,

C_{rd} = die casting machine and operator rate, \$/hr,

and t_m = die casting machine cycle time, s.

The hourly operating rate of a die casting machine, including the operator rate, can be approximated by the following linear relationship:

$$C_{rd} = m_1 * F_c + b_d \; , \qquad (3.3)$$

where: m_1 = slope of the line, \$/kN,

F_c = die casting machine clamp force, kN, and

b_d = minimum casting machine rate, \$/hr.

This relationship was arrived at through examination of the machine hourly rate data [18] shown in Fig. 3.1. The equation of this line, for machine sizes less than 5.3 MN, is:

$$C_{rd} = 0.00337 * F_c + 54 \; , \qquad (3.4)$$

and b_d therefore has a value of 54 \$/hr. For machine sizes greater than 5.3 Mn, the machine hourly rate equation is:

$$C_{rd} = 0.000899 * F_c + 25 \; .$$

The form of these relationships is supported by the nature of the variation of die casting machine capital costs with rated clamp force values as shown in (Figs. 3.2 and 3.3). This machine cost data, obtained from five machine makers shows a linear relationship between clamp force and machine costs for hot or cold-chamber machines up to 15 MN. However, it should be noted that very large cold-chamber machines in the range of 15 to 30 MN are associated with greatly increased cost (see Fig. 3.4). For these machines,

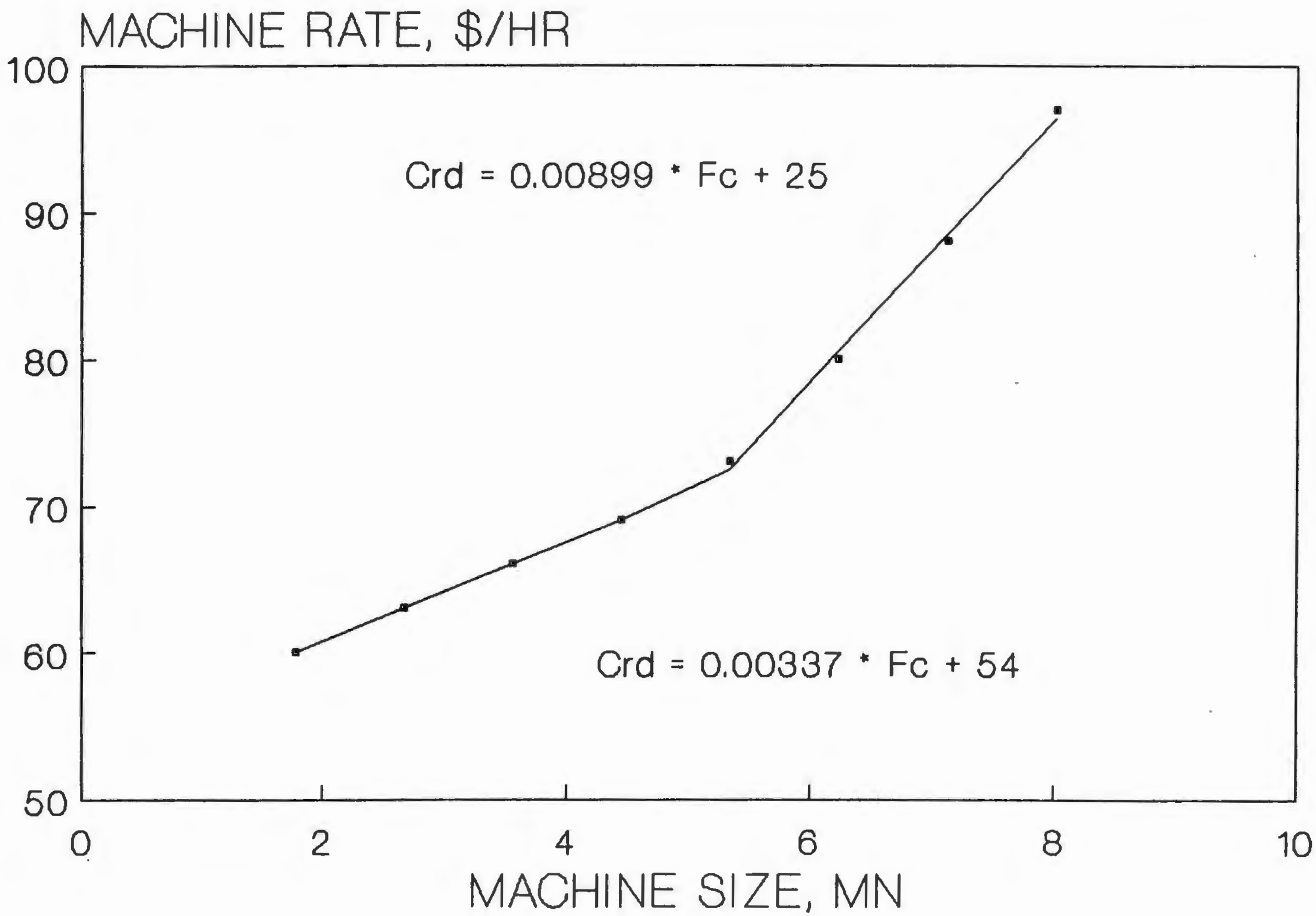

Figure 3.1: Die Casting Machine Operating Rates

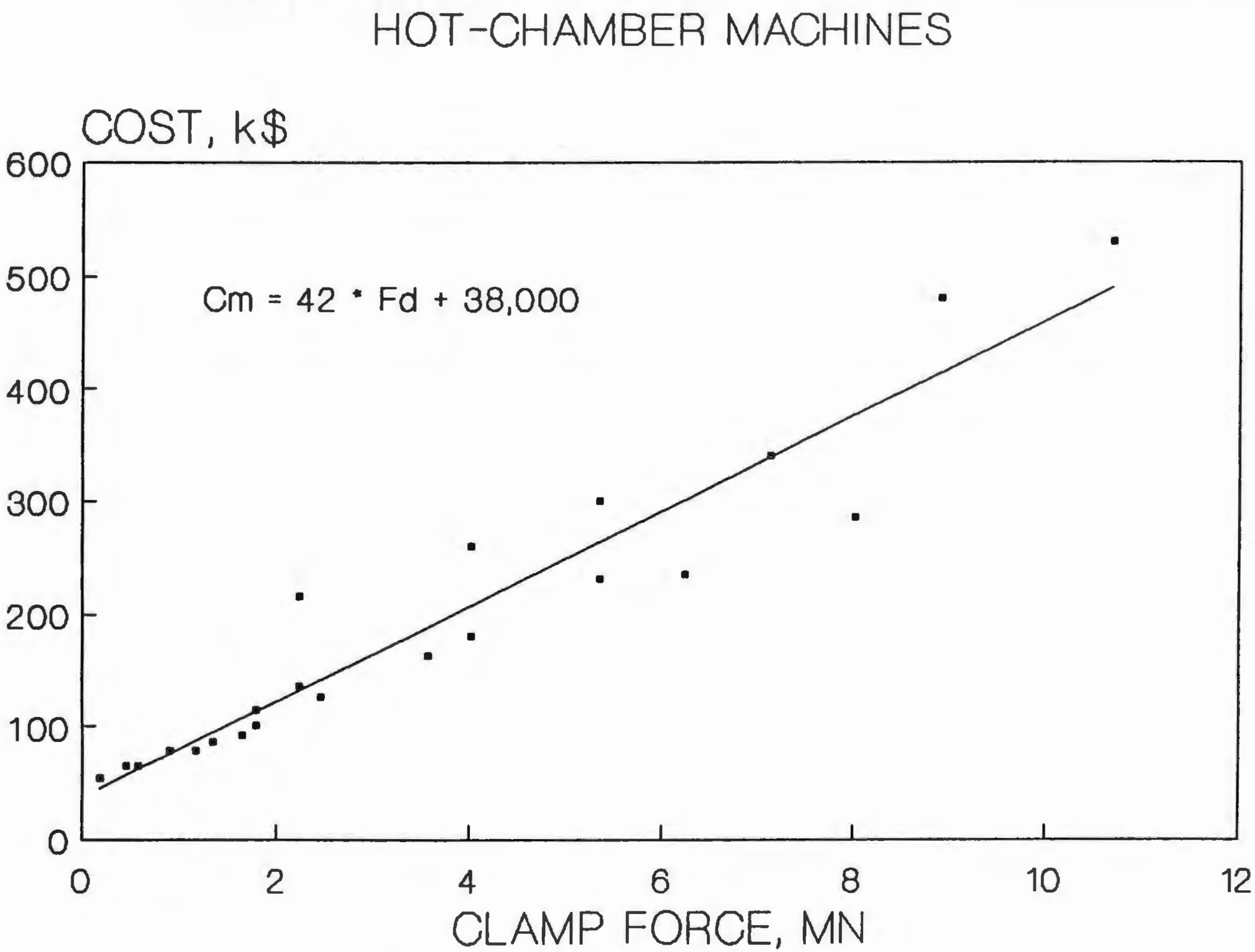

Figure 3.2: Hot-Chamber Machine Costs

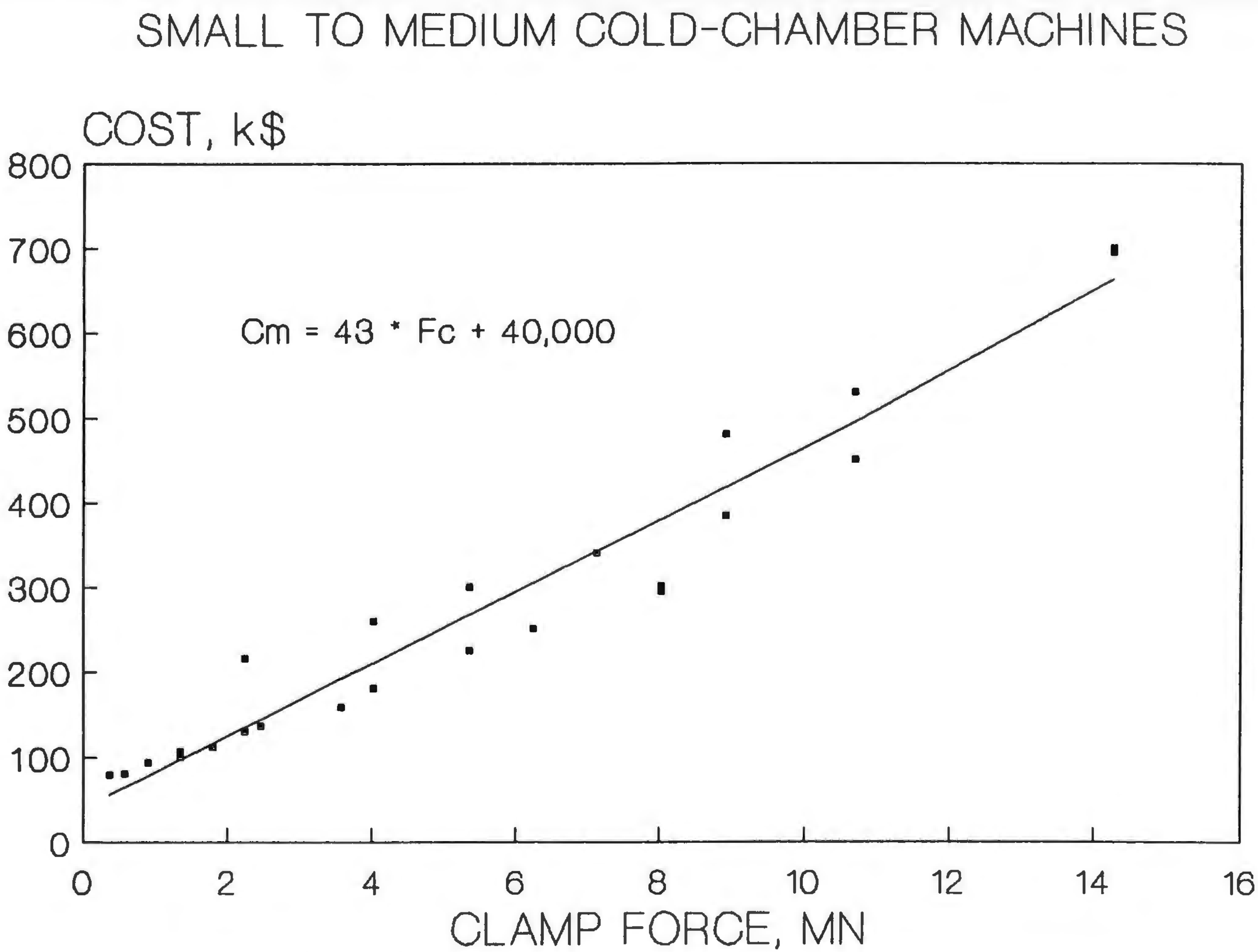

Figure 3.3: Cold-Chamber Machine Costs - Small to Medium Machines

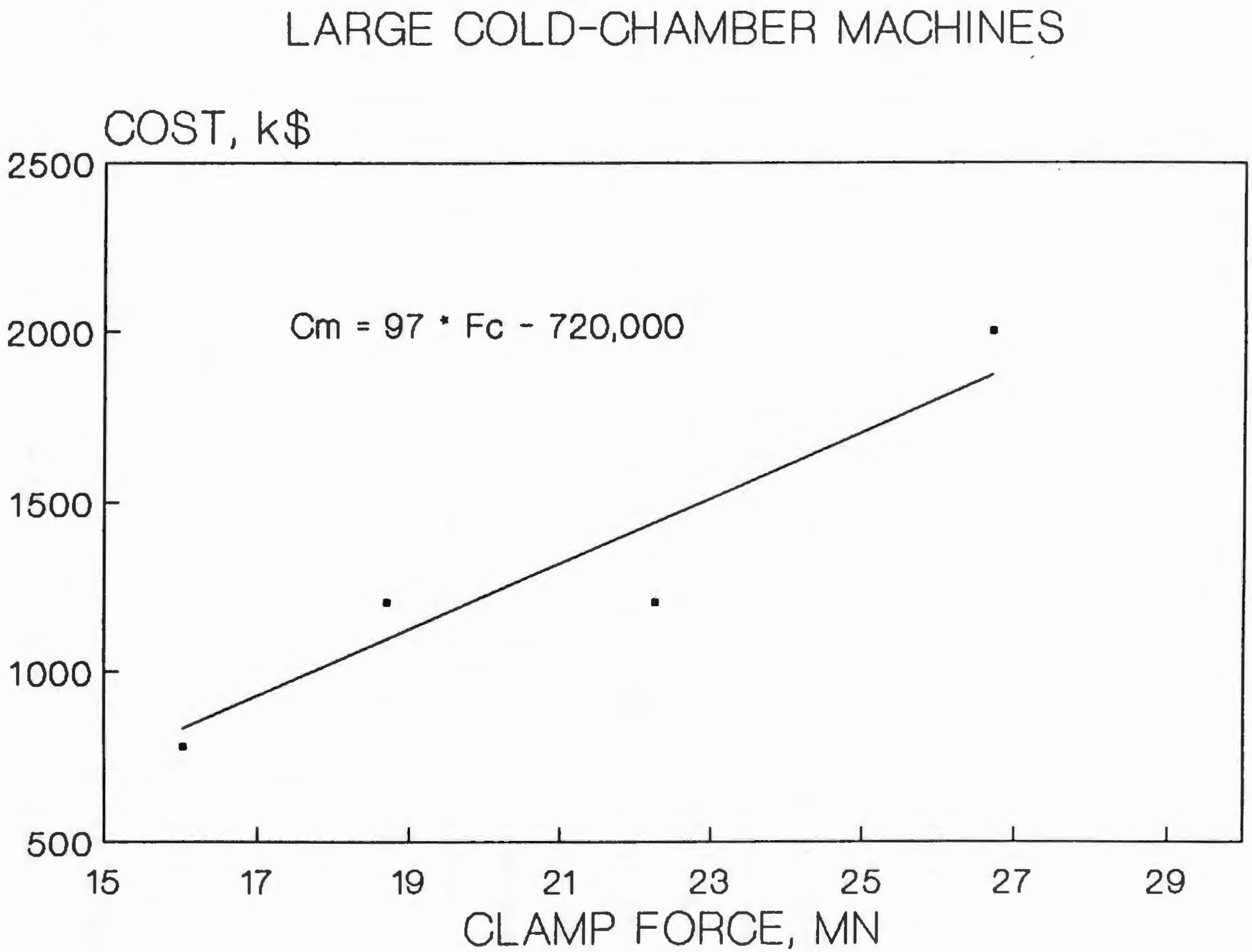

Figure 3.4: Cold-Chamber Machine Costs - Large Machines

the smooth relationship results obtained in this section should be applied with caution.

The cost of trimming, CTR, can be represented by the following equation:

$$CTR = \frac{NT}{n_c} C_{rt} * t_p * \frac{1 \text{ hr}}{3600 \text{ s}} , \qquad (3.5)$$

where: C_{rt} = trim press and operator rate, \$/hr, and

t_p = trimming cycle time, s.

The hourly rate for trimming is approximated by a constant value for all size trim presses. This is done because the cost of trim presses is relatively low due to the small forces, and therefore small capacity presses, necessary in the trimming of die casting alloys. Therefore, C_{rt} is clearly dominated by the hourly rate of the trim press operator rather than by the cost of the press itself.

The trimming cycle time can be represented by the following equation:

$$t_p = t_{p0} + n_c * \Delta t_p , \qquad (3.6)$$

where: t_{p0} = trimming cycle time for a single-aperture trimming operation for a single part, s,

and Δt_p = additional trimming cycle time for each aperture in a multi-aperture trimming die, mainly due to increased loading time.

A more detailed analysis of die casting trimming cycle times can be found in Section 5.1.1.

The cost of a multi-cavity die casting die, C_{dn}, relative to the cost of a single-cavity tool, C_d, follows a relationship similar to that of injection molding dies. Based on data from Reinbacker [19], this relationship can be represented as the following power law:

$$C_{dn} = C_d * n_c^{md} , \qquad (3.7)$$

where: C_d = cost of a single-cavity die casting die, \$,

and m_d = multi-cavity die cost exponent.

Collection of industrial data has indicated that the value of the multi-cavity cost exponent usually lies between the values 0.7 and 0.8.

The cost of a multi-aperture trim die, C_{tn}, relative to the cost of a single aperture trim die, C_t, follows a similar relationship, namely:

$$C_{tn} = C_t * n_c^{mt} , \qquad (3.8)$$

where: C_t = cost of a single-aperture trim die, \$, and

m_t = multi-aperture trim die cost exponent.

It is assumed that the cost exponent for multi-aperture trim tools is the same as that for multi-cavity die casting dies, referred to simply as m from this point on.

The equation for the total alloy cost, CA, is:

$$CA = NT * C_a \,, \qquad (3.9)$$

where: C_a = alloy cost for each casting, $.

Compiling the previous equations, Eqn. (3.1) can be written as follows:

$$CT = \frac{NT}{n_c} C_{rd} * t_m * \frac{1}{3600} + \frac{NT}{n_c} C_{rt} * t_p * \frac{1}{3600}$$

$$+ C_d * n_c^m + C_t * n_c^m + NT * C_a \,.$$

Further substitution gives:

$$CT = \frac{NT}{n_c} (m_1 * F_c + b_d) * t_m * \frac{1}{3600}$$

$$+ \frac{NT}{n_c} C_{rt} * (t_{p0} + n_c * \Delta t_p) * \frac{1}{3600}$$

$$+ (C_d + C_t) * n_c^m + NT * C_a \qquad (3.10)$$

If full die casting machine clamp force utilization is assumed, then:

$$F_c = n_c * f$$

or: $$n_c = F_c/f \,, \qquad (3.11)$$

where F_c = die casting machine clamp force, kN, and

f = separating force on one cavity, kN.

Substituting this gives:

$$
\begin{aligned}
CT = {} & NT(m_1 * f + b_d * f/F_c) * t_m * (1/3600) \\
& + NT * C_{rt} * t_{p0} * f/F_c * (1/3600) \\
& + NT * C_{rt} * \Delta t_p * (1/3600) \\
& + (C_d + C_t) * (F_c/f)^m + NT * C_a .
\end{aligned}
$$

In order to find the number of cavities that gives the lowest cost for any given die casting machine size, the derivative is taken with respect to the clamp force and is equated to zero, giving:

$$
\frac{dCT}{dF_c} = - \frac{NT * f}{3600 * F_c^2} (b_d t_m + C_{rt} t_{p0})
$$

$$
+ m * \frac{F_c^{(md-1)}}{f^{md}} * (C_d + C_t) = 0 . \tag{3.12}
$$

Rearranging gives:

$$
\frac{NT(b_d t_m + C_{rt} t_{p0})}{3600 * m(C_d + C_t)} = \frac{F_c^{(m-1)}}{f^m} * \frac{F_c^2}{f} ,
$$

or

$$
n_c^{(m+1)} = \frac{NT(b_d t_m + C_{rt} t_{p0})}{3600 * m(C_d + C_t)} , \tag{3.13}
$$

as the equation for the most economic number of die cavities for any given die casting task.

If the preceding analysis had not considered the cost due to the trimming operation, the resulting equation for the optimum number of cavities would have been the following:

$$n_c^{(m+1)} = \frac{NT * b_d * t_m}{3600 * m * C_d} . \qquad (3.14)$$

In the following example, the optimum number of cavities will be determined using both Eqn. (3.13) and Eqn. (3.14) for comparison.

EXAMPLE:

A die cast component has an estimated die casting cycle time of 20 s for a single-cavity mold and an estimated 7 s trimming cycle time for a single-aperture trim die. The cost of a single-cavity mold for this part has been estimated to be \$10,000 and the trim die has been estimated to be \$2,000. The optimum number of cavities for production volumes of 100,000, 250,000, and 500,000 are to be found using the data given in the previous analysis.

$$\begin{aligned} b_d &= 46 \text{ \$/hr} \\ C_{rt} &= 35 \text{ \$/hr} \\ m &= 0.7 \\ t_m &= 20 \text{ s} \\ t_{p0} &= 7 \text{ s} \\ C_d &= \$10{,}000 \\ C_t &= \$2{,}000 \end{aligned}$$

Using Eqn. (3.13) when NT = 100,000 components, gives:

$$n_c^{(1.7)} = 100{,}000(46*20 + 35*7)/(3600*0.7*12{,}000)$$

$$n_c = 2.2$$

Similarly, for 250,000 components, $n_c = 3.8$, and for 500,000 components, $n_c = 5.7$. These numbers indicate that for production volumes of 100,000, 250,000, and 500,000, dies with cavity numbers of 2, 4, and 6, would be optimum.

If the same calculations were done using Eqn. (3.14), n_c values of 2.14, 3.67, and 5.52, would result for production volumes of 100,000, 250,000, and 500,000, respectively. When these figures are rounded to the nearest practical number of cavities, the results from using Eqn. (3.13) and Eqn. (3.14) are identical.

Whether considering trimming costs or not, the total number of components can be related to a ratio of basic casting cost to tool cost as shown in Fig. 3.5. This ratio can be shown to be:

$$R1 = \frac{b_d * t_m + C_{rt} * t_{p0}}{3600 * (C_d + C_t)},$$

and

$$R2 = \frac{b_d * t_m}{3600 * C_d},$$

where: R1 = ratio of basic casting cost to tool cost including trimming,

and R2 = ratio of basic casting cost to tool cost excluding trimming.

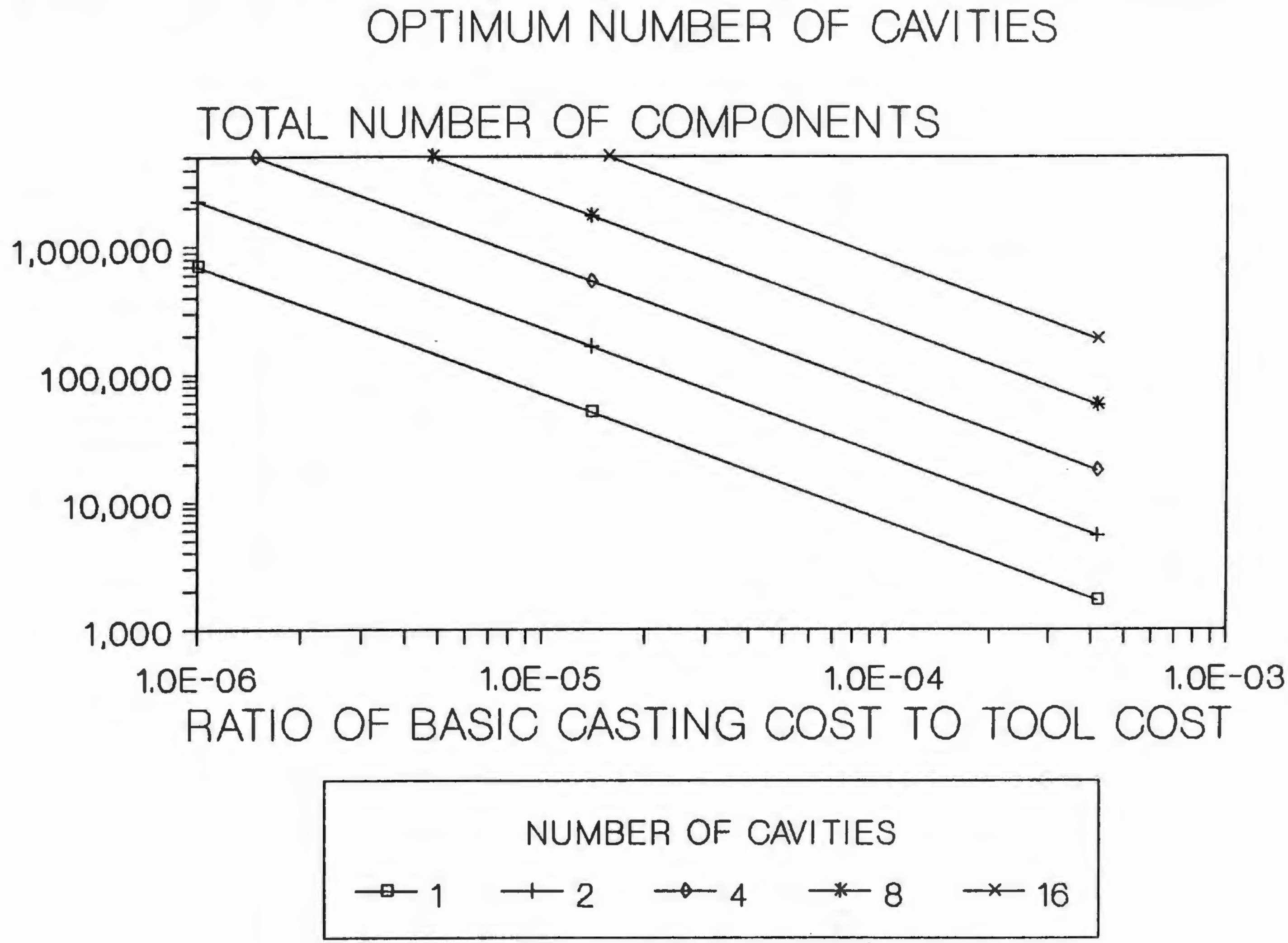

Figure 3.5: Optimum Number of Cavities

From Eqns. (3.13) and (3.14), the total number of parts, necessary for the economic production of castings in a die with n_c cavities is then:

$$NT = \frac{n_c^{(m+1)} * m}{R1} ,$$

and

$$NT = \frac{n_c^{(m+1)} * m}{R2} .$$

Once the most economical number of cavities has been determined for a particular die casting task, the physical constraints of the equipment must be examined. The first consideration is that of the number and position of sliding cores in the die.

Sliding cores must be located in the die such that they may be retracted, and such that there is space for their driving mechanisms. Cavities that require sliding cores on four sides are limited to single-cavity dies as shown in Fig. 3.6. Similarly, cavities with cores on three sides are limited to two-cavity dies (Fig. 3.7). Cavities containing core slides on two sides are restricted to either two or four-cavity dies, depending on the angle between slides (Figs. 3.8 and 3.9). If this angle is 180 degrees then a two-cavity die must be used. When the angle between the two core slides is 90 degrees, it is possible to fit four cavities into a die.

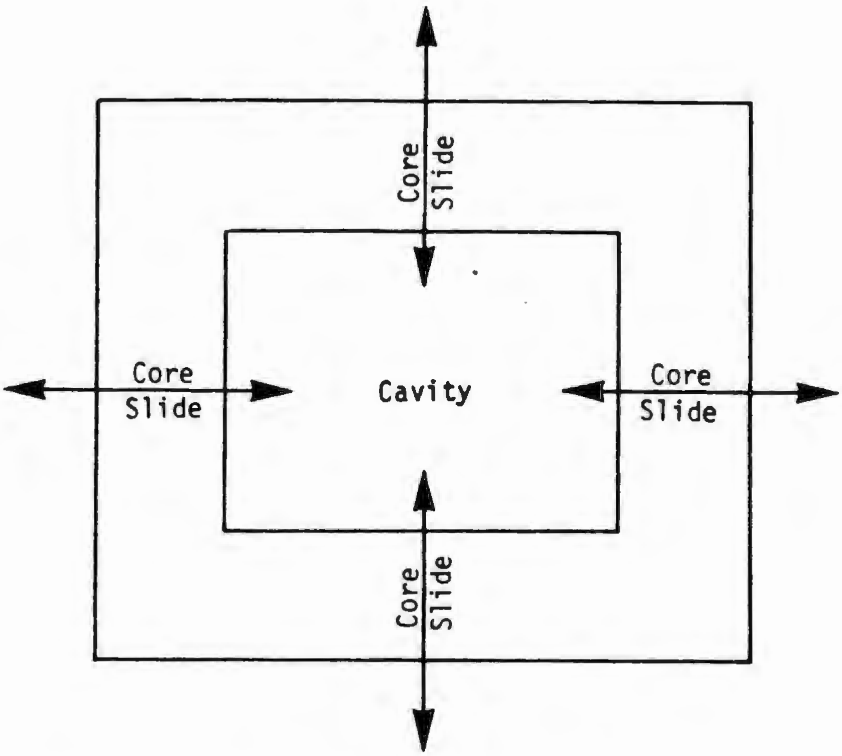

Figure 3.6: Castings That Require Moving Cores on all Four Sides are Usually Restricted to Single Cavity Dies (Reprinted from [11])

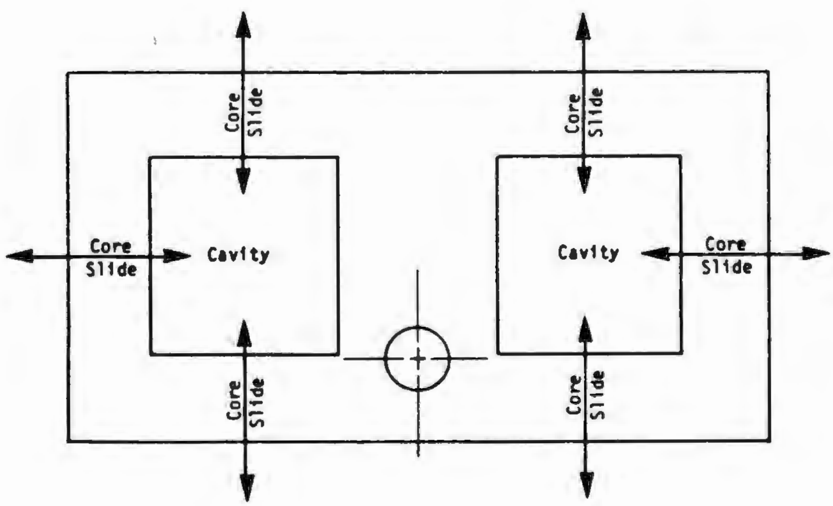

Figure 3.7: Two Cavities with Three Sliding Cores can Often be Placed on one Die (Reprinted from [11])

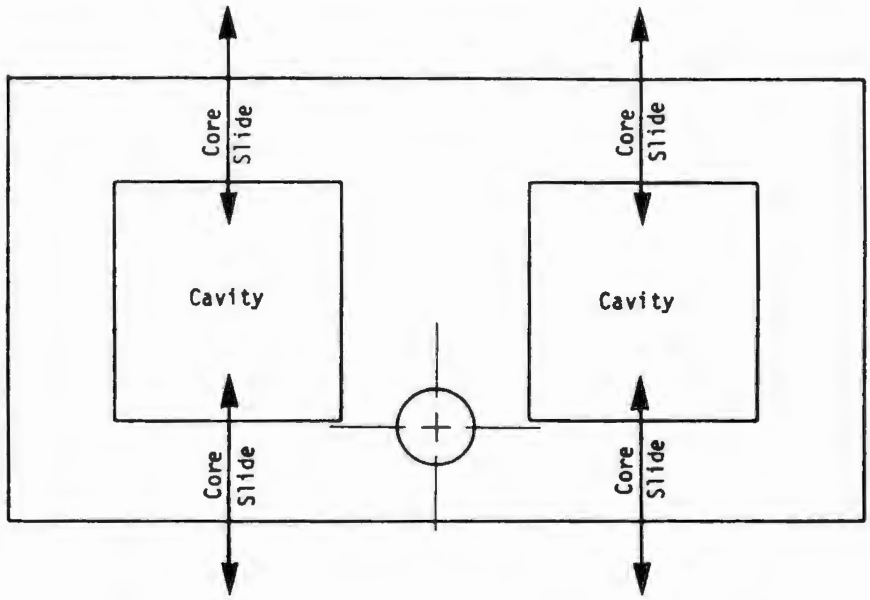

Figure 3.8: Cavities Having Two Core Slides at 180 Degrees are Limited to Two Per Die (Reprinted from [11])

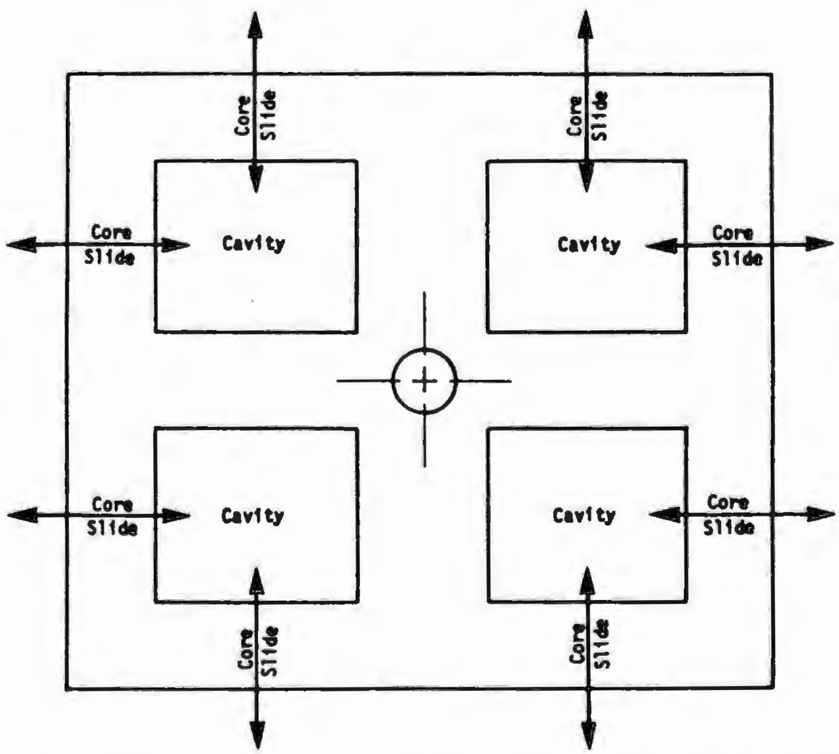

Figure 3.9: Four Cavities, Each With Two Core Slides at 90 Degrees can be Packed into a Single Die if Necessary (Reprinted from [11])

The remaining constraints are on the die casting machine and trim press to be used for the task. The die casting machine must be large enough to provide the required clamp force, as well as to provide a platen area, shot volume, and die opening large enough for the specified casting arrangement. Similarly, the bed area of the trim press must be large enough to accommodate the area of the shot. If the available machines and presses can not meet all of these constraints, then the number of cavities must be lowered until the corresponding machine size falls within the range of available machines. The process of determining the appropriate machine size will be covered in detail in the next section.

3.2 Determination of Appropriate Machine Size

Several factors must be considered when choosing the appropriate machine size with which to cast a particular die cast component. These factors include the machine performance, as well as the dimensional constraints imposed by the machine. The most important machine performance capability to be considered is the machine clamping force. Dimensional factors that must be considered include the available shot volume capacity, the die opening stroke length, also called clamp stroke, and the platen area.

3.2.1 Required Machine Clamp Force

Die casting machines are primarily specified on the basis of machine clamping force. In order to prevent the die halves from separating, the clamp force, F_c, exerted by the machine on the die, must be greater than the opposing force, F_m, of the molten metal on the die during injection, or:

$$F_c > F_m \ . \tag{3.15}$$

The actual clamp force of a machine may be lower than the rated clamp force due to energy losses in the system and flexing of some of the machine elements. For this reason, an efficiency factor, η, must be applied, yielding the following relationship:

$$F_c * \eta > F_m . \tag{3.16}$$

Industrial research shows 0.7 to be an appropriate value for the efficiency of die casting machines.

For a given die casting task, the force exerted by the molten metal may be represented as follows:

$$F_m = P_m * A_{pt} , \tag{3.17}$$

where: F_m = force of molten metal on die, kN,

P_m = molten metal pressure, MPa, and

A_{pt} = total projected area of molten metal within the die, mm^2.

3.2.1.1 Total Projected Area

The total projected area, A_{pt}, is the area of the cavities, feed system, and overflow wells, taken normal to the direction of die opening and can be represented by the following equation:

$$A_{pt} = A_{pc} + A_{po} + A_{pf} , \tag{3.18}$$

where: A_{pc} = projected area of cavities, mm^2,

A_{po} = projected area of overflow wells, mm^2, and

A_{pf} = projected area of feed system, mm^2.

It can be seen from Figs. 3.10 and 3.11 that the projected areas of the overflow wells and feed system represent a

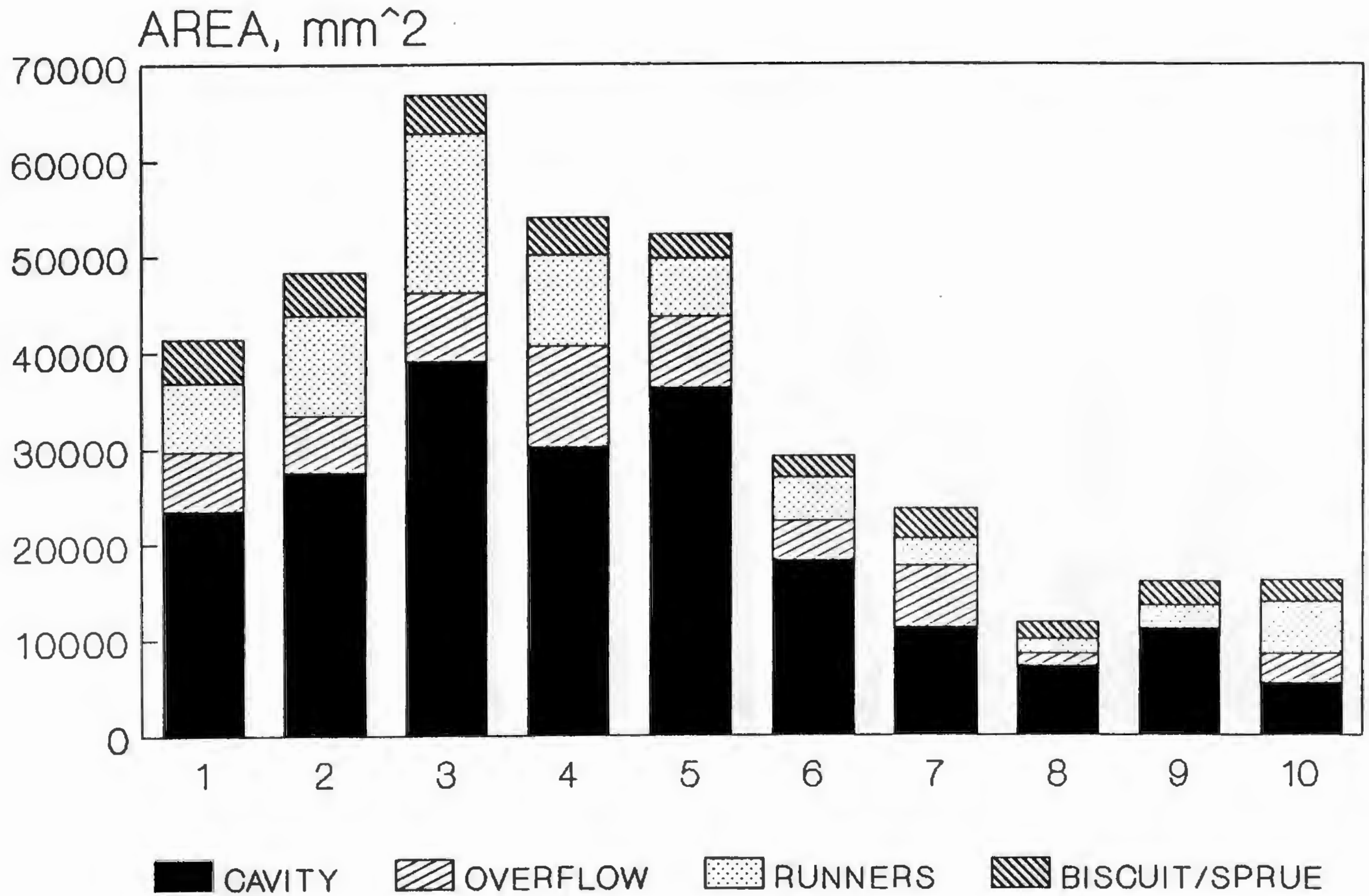

Figure 3.10: Breakdown of Shot Projected Area for Ten Sample Die Castings

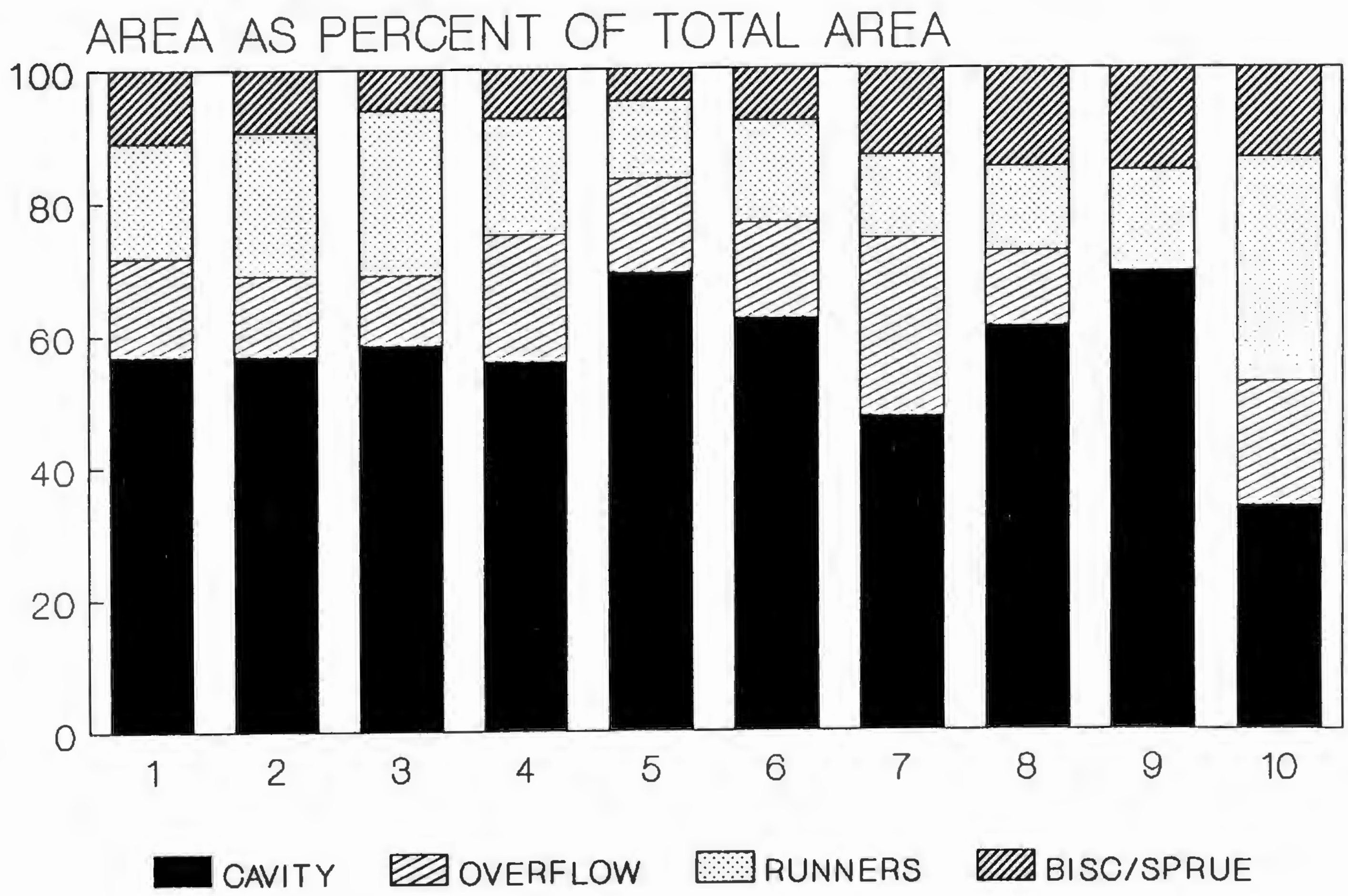

Figure 3.11: Breakdown of Projected Areas as a Percentage of Total Shot Area for Ten Sample Die Castings

significant portion of the total projected area and that determination of these areas is therefore necessary.

The projected area of the cavities is the product of the projected area of the part to be die cast and the number of cavities. The projected area of the overflows can then be estimated by using a relationship derived from data obtained from sample die casting shots supplied by Kennedy Die Castings [21], as described below. The projected areas of the overflow wells as a percentage of the projected area of the cavities was plotted against average wall thickness as shown in Fig. 3.12. The resulting relationship for A_{po} is the following:

$$A_{po} = A_{pc} * w^{(-0.466)} * e^{(3.76)} / 100. \qquad (3.19)$$

where: A_{pc} = projected area of cavities, mm^2, and

w = average wall thickness of the casting, mm.

The projected area of the feed system includes the projected area of the runners and either the projected area of the sprue, in the hot-chamber process, or the projected area of the biscuit, in the cold-chamber process, as shown in the following relationship:

$$A_{pf} = A_{pr} + A_{psb} \, . \qquad (3.20)$$

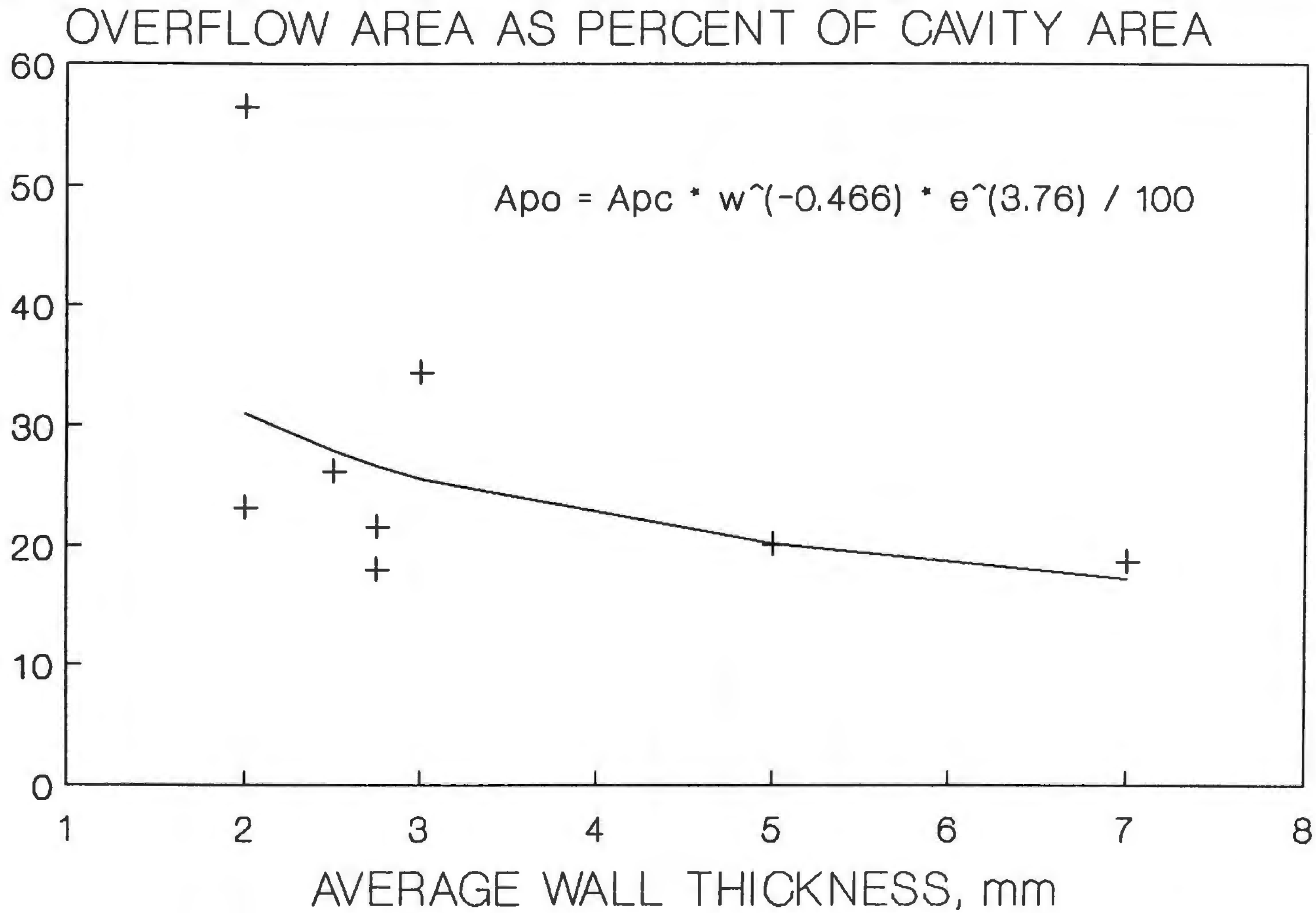

Figure 3.12: Overflow Well Projected Area as a Percentage of Cavity Projected Area, as a Function of Average Wall Thickness

where: A_{pr} = projected area of runners, mm^2, and

A_{psb} = projected area of sprue or biscuit, mm^2.

The projected area of the runners is related to the wall thickness of the casting in a similar manner to the overflow wells as shown in Fig. 3.13. The resulting relationship for A_{pr} is the following:

$$A_{pr} = A_{pc} * w^{(-0.376)} * e^{(3.74)} / 100 . \qquad (3.21)$$

If a hot-chamber die casting machine is used, the projected area of the sprue must be calculated. According to one die manufacturer [22] sprues are available in small, medium, and large, with diameters of 38 mm, 45 mm, and 64 mm, respectfully. On hot-chamber machines, the plunger tip diameter does not enter into the projected area calculations because the area of the plunger is not projected onto the die (see Figs. 2.1, 2.14).

If a cold-chamber machine is used, the projected area of the biscuit is determined by the diameter of the plunger used. A range of plunger tip diameters are usually available for each machine. Plunger sizes are chosen to obtain a desired metal injection pressure. The plunger area determines the magnitude of the pressure drop from the hydraulic cylinder to the desired molten metal pressure in the shot sleeve and the die cavity as shown in Fig. 3.14. Since the force remains constant from the hydraulic cylinder

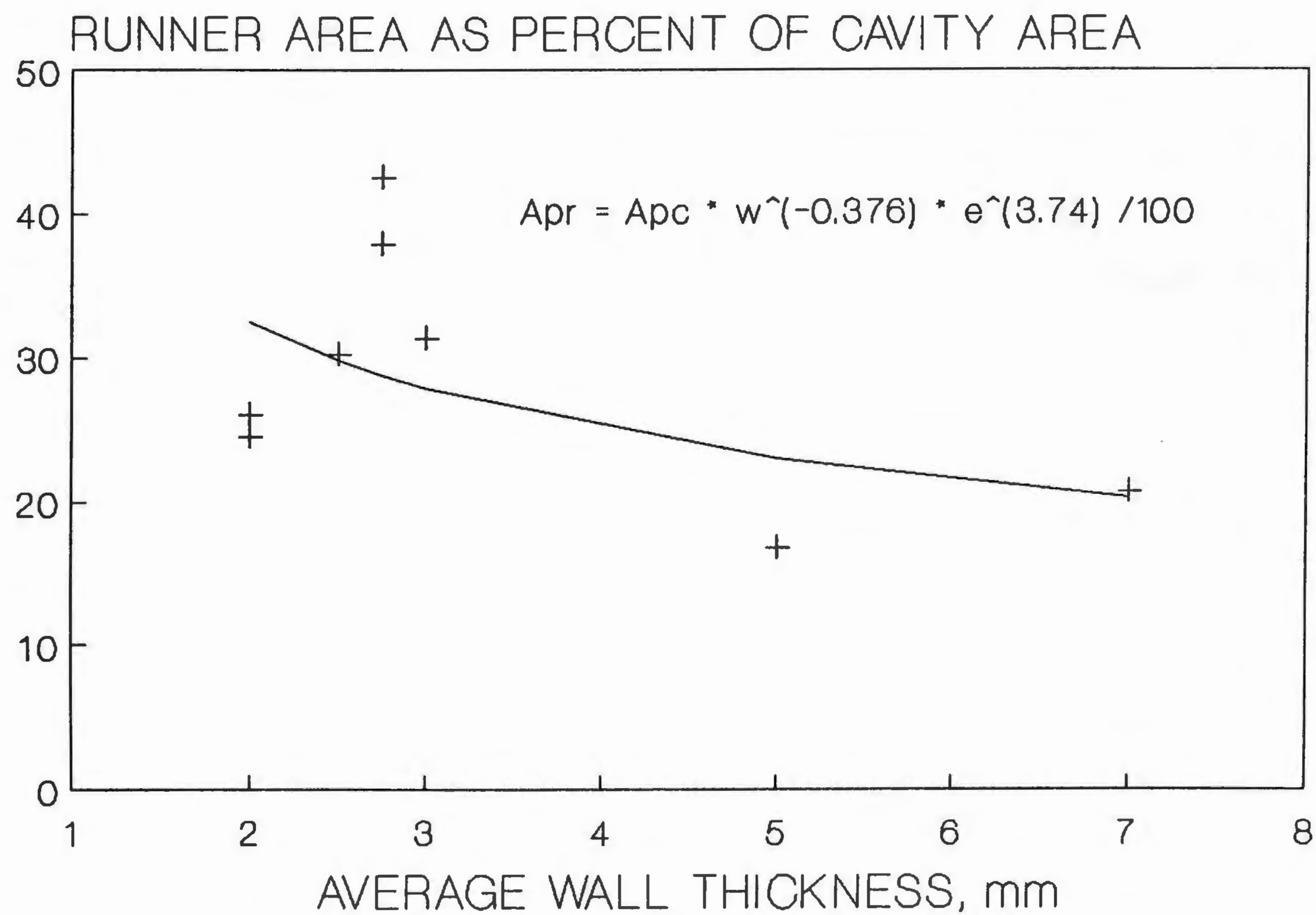

Figure 3.13: Runner Projected Area as a Percentage of Cavity Projected Area, as a Function of Average Wall Thickness

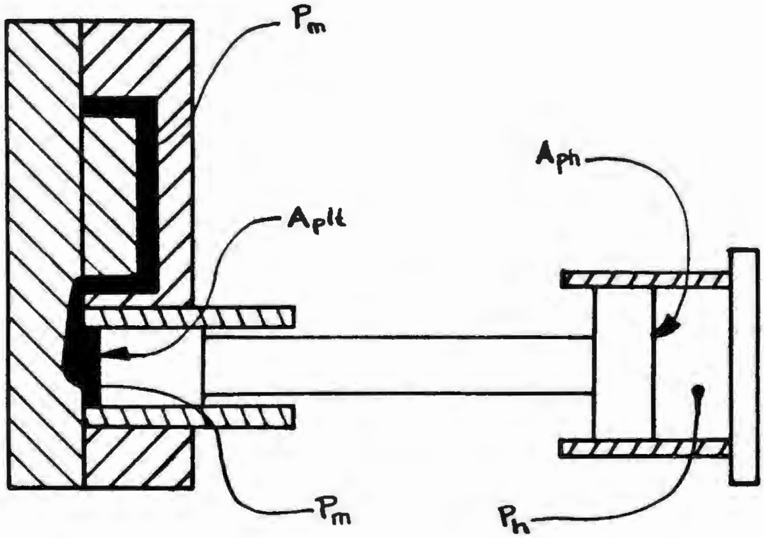

Figure 3.14: Pressure and Cylinder Area Situation in the Cold-Chamber Process

to the shot sleeve, except for losses due to friction, the pressure in the shot cylinder is inversely proportional to the area of the plunger tip as seen in the following relationship:

$$F_1 = P_h * A_{ph} = P_m * A_{plt} , \qquad (3.22)$$

where: F_1 = injection system force, N,
P_h = hydraulic cylinder pressure, MPa,
A_{ph} = piston head area, mm^2,
P_m = molten metal pressure, MPa, and
A_{plt} = plunger tip area, mm^2.

Since the hydraulic pressure and the piston head area are not yet known, an estimated plunger tip diameter may be chosen from Table 3.1 for the purpose of calculating A_{psb} which is simply the area of a circle with this diameter. Once the machine size is determined by the procedure outlined in this section, the actual plunger diameter, obtained from a machine database such as Table 3.2 or calculated using an estimating relationship, can be used to re-calculate the appropriate machine size in an iterative procedure. The relationship for estimating the range of plunger tip diameters available on cold-chamber machines was developed from the data in Table 3.1 as shown in Fig. 3.15. The resulting equations for minimum and maximum plunger tip diameters are as follows:

CLAMP FORCE (kN)	PLUNGER TIP DIAMETERS, mm					
	MIN.					MAX.
577	35					38
1780	40					57
2225	38	44	51	57	64	70
3560	49					70
4005	51	57	64	70	76	83
5340	56					79
6230	57	64	70	76	83	89
7120	64					127
8010	57	64	70	76	83	89
8010	65					91
8900	57	64	70	76	83	89
8900	64					127
10680	83	89	95	102	108	114
10680	76					108
14240	114	121	127	133	140	146
16020	92					130
18690	114	121	127	133	140	146
26700	114	121	127	133	140	146

Table 3.1: Plunger Tip Diameters for Cold-Chamber Machines

COLD-CHAMBER DIE CASTING MACHINES

CLAMP FORCE (kN)	MAXIMUM SHOT VOLUME (cc)	PLUNGER TIP DIAMETER (mm)	HYDRAULIC CYLINDER PRESSURE (MPa)	HYDRAULIC CYLINDER DIAMETER (mm)	MOLTEN METAL PRESSURE (MPa)
356	126	32	10.3		
577	213	38	10.3	70	34.8
1335	437	51	10.3		
1780	672	57	8.6	95	24.4
2225	777	70		121	
2225			10.3	102	
2448	806	64	12.4		
3560	1176	70	10.3	108	24.5
4005	1680	83		165	
4005			10.3	127	
5340	1882	79	10.3	121	24.1
5340			10.3	140	
6230	1932	89		181	
7120		127	10.3	152	14.9
8010	2436	89		181	
8010	3226	91	10.3	140	24.4
8900	3276	89		229	
8900			10.3	152	
10680	5397	114		229	
10680	5846	108	10.3	165	24.3
10680			10.3	178	
14240	11256	146		279	
14240			10.3	203	
16020	9038	130	11.4	191	24.4
18690	11634	146		279	
22250			10.3	229	
26700	11634	146		279	

Table 3.2: Cold-Chamber Die Casting Machine Specifications

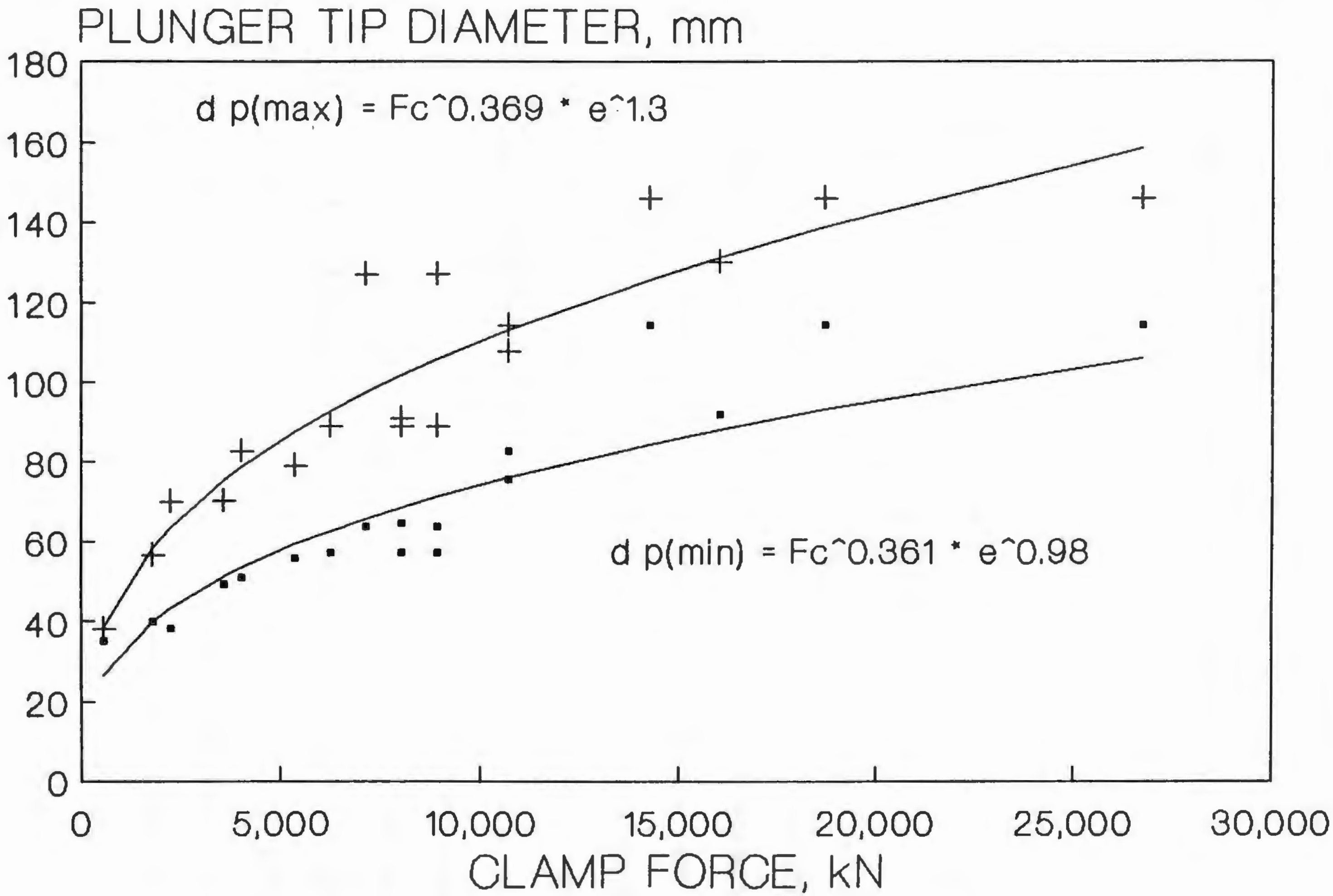

Figure 3.15: Plunger Tip Diameters as a Function of Machine Clamp Force for Cold-Chamber Machines

$$d_{p(max)} = F_c^{0.369} * e^{1.3} \text{ , and} \tag{3.23}$$

$$d_{p(min)} = F_c^{0.361} + e^{0.98} \text{ ,} \tag{3.24}$$

where: $d_{p(max)}$ = maximum plunger tip diameter, mm,
$d_{p(min)}$ = minimum plunger tip diameter, mm, and
F_c = machine clamp force, kN.

3.2.1.2 Cavity Pressure

As previously mentioned, the cavity pressure, equal to the metal pressure, is dependent upon the hydraulic pressure, the piston head area, and the plunger tip area. As with the determination of the plunger tip diameter, an iterative process must be employed in order to determine the metal pressure. Typical average metal pressures may be used to determine the necessary clamp force of the machine. Once the machine size is determined, hydraulic cylinder and plunger tip specifications, as shown in Tables 3.2 and 3.3, can be used to determine the actual maximum metal pressure. This pressure is the maximum available metal pressure for the specific machine/plunger situation. Hydraulic pressures may be adjusted on each machine if the casting situation calls for lower metal pressures. The maximum metal pressure may then be used to recalculate the required clamp force.

Typical cavity pressures for casting aluminum in cold-chamber machines and zinc in hot-chamber machines, obtained from Kennedy Die Castings [21], are 89.6 MPa and 20.7 MPa,

HOT-CHAMBER DIE CASTING MACHINES

CLAMP FORCE (kN)	MAXIMUM SHOT VOLUME (cc)	PLUNGER TIP DIAMETER (mm)	HYDRAULIC CYLINDER PRESSURE (MPa)	HYDRAULIC CYLINDER DIAMETER (mm)	MOLTEN METAL PRESSURE (MPa)
178	185	38	6.9		17.2
445	504	51	10.3		35.7
577	1310	64	12.4	83	30.4
890	504	51	12.1		35.8
1157	1310	64	12.4	83	27.3
1335	739	57	10.3		38.5
1643	1613	70	12.4	89	31.7
1780	1596	70	12.1		35.1
1780	1294				19.4
2225	1050	76		79	
2225			10.3	102	
2448	2184	76	12.4		36.2
3560	2016				19.4
4005	1596			79	
4005			10.3	127	
5340	3595				19.4
5340			10.3	152	
6230	4032			92	
7120			10.3	178	
8010	4032			92	
8900			10.3	178	
10680			10.3	178	

Table 3.3: Hot-Chamber Die Casting Machine Specifications

respectively. For cold-chamber machines, the metal has partially solidified to a slushy consistency by the time it enters the die cavity and therefore the effective pressure of the metal contributing to die separation is approximately 70 percent of this pressure, or 62.7 MPa. Since the aluminum cavity pressure is significantly higher than the zinc cavity pressure, cold-chamber machines commonly use intensifiers, which are based on hydraulic accumulator systems, to achieve the higher pressures. Some machine makers suggest that the unintensified metal pressures may be used to calculate machine clamp forces because intensification does not start until the metal is fully injected into the cavity and a skin of solidified material has formed on the cavity wall. This skin contains the intensified pressure so it does not contribute to the separation of the dies. Other industrial sources indicate that it is safer to use the intensified pressure for clamp force calculations, stating that this over-estimation of the clamp force will compensate for such elements as the contribution of flash to the total projected area of the shot. For these reasons, intensified pressures are used in the present procedure.

3.2.2 Physical Constraints of the Equipment

Once the required machine clamp force has been determined, the available machine specifications must be examined. Several physical constraints must be met in order for a particular machine to be specified. These constraints are the shot volume capacity, the die opening distance, and the platen area. Tables for specific machine characteristics are contained within this chapter.

3.2.2.1 Shot Volume

As previously mentioned, a variety of plunger tip diameters is available for each machine. These plunger tips determine not only the pressure on the molten metal, but also the volume in the shot sleeve available for the molten metal. The volume of molten metal necessary must first be calculated. The available volume is the product of the plunger tip diameter previously chosen and the shot sleeve length. In the cold-chamber process, shot cylinders are usually filled to approximately 60% of their volume [23]. Shot volume capacities may also be listed in some die casting machine specifications.

The shot volume necessary can be represented by the following equation:

$$V_s = V_c + V_o + V_f ,$$

where: V_s = total shot volume, mm^3,

V_c = volume of cavities, mm^3

V_o = volume of overflow wells, mm^3, and

V_f = volume of feed system, mm^3.

As with the cavity projected area, the volumes of the overflow wells and the feed system represent a significant portion of the total shot volume, as shown in Figs. 3.16 and 3.17. The cavity volume is, as with cavity projected area, the product of the volume of the part to be cast and the number of cavities. Sample part volume data, similar to the projected area data, was collected, as shown in Fig. 3.18, resulting in the following relationships for the volume of the overflow wells:

$$V_o = V_c * w^{(-1.268)} * e^{(4.38)} / 100 \ . \quad (3.25)$$

The volume of the feed system, V_f, can be represented as:

$$V_f = V_r + V_{sb} \ ,$$

where V_r = volume of runners, mm^3, and

V_{sb} = volume of sprue or biscuit, mm^3.

As with the overflow volume, runner volume data was collected as shown in Fig. 3.19 resulting in the following relationship:

$$V_r = V_c * w^{(-1.09)} * e^{(4.64)} / 100 \ . \quad (3.26)$$

The volume of the biscuit in the cold-chamber process is the multiple of the projected area of the biscuit,

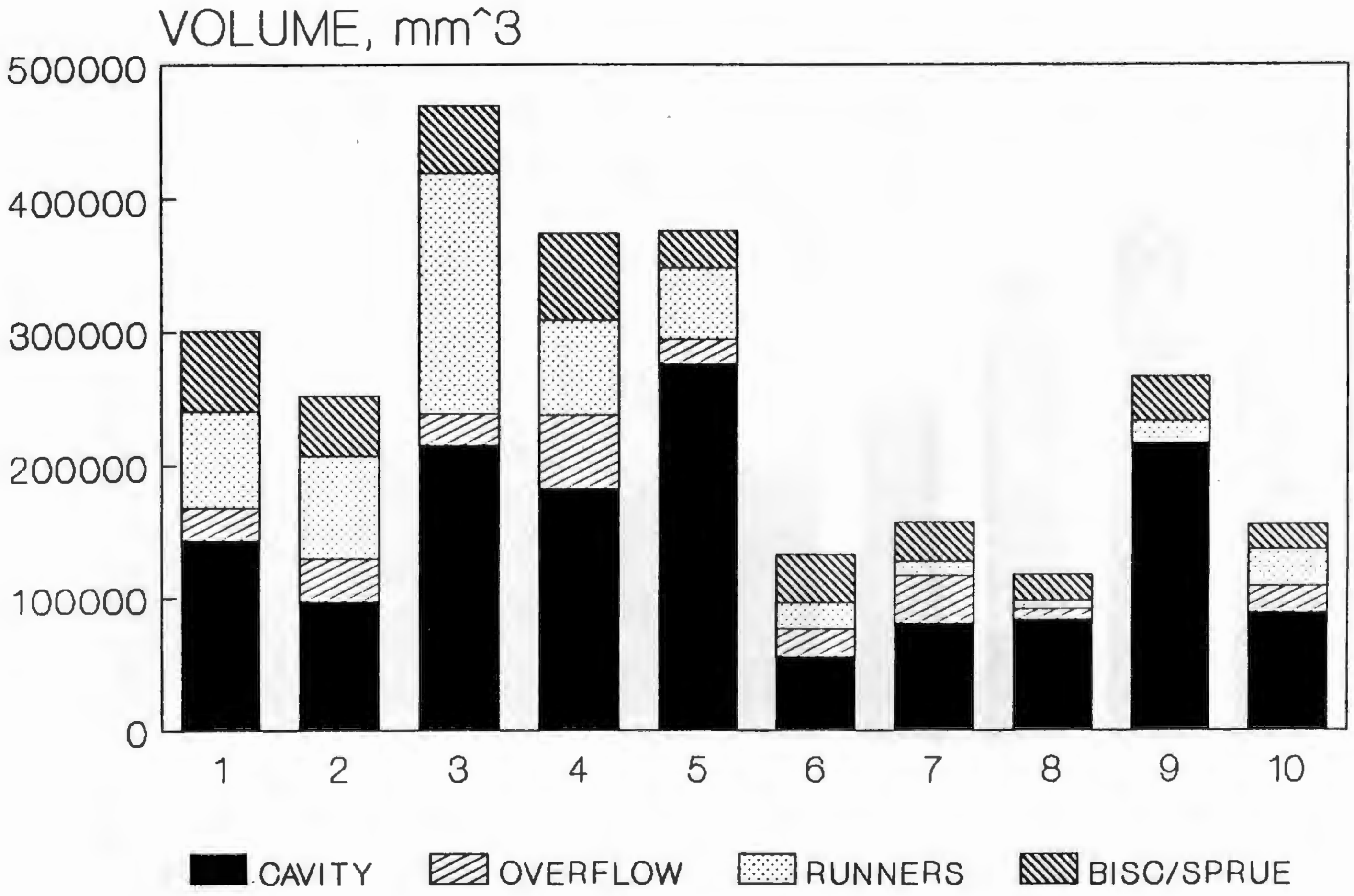

Figure 3.16: Breakdown of Shot Volume for Ten Sample Die Castings

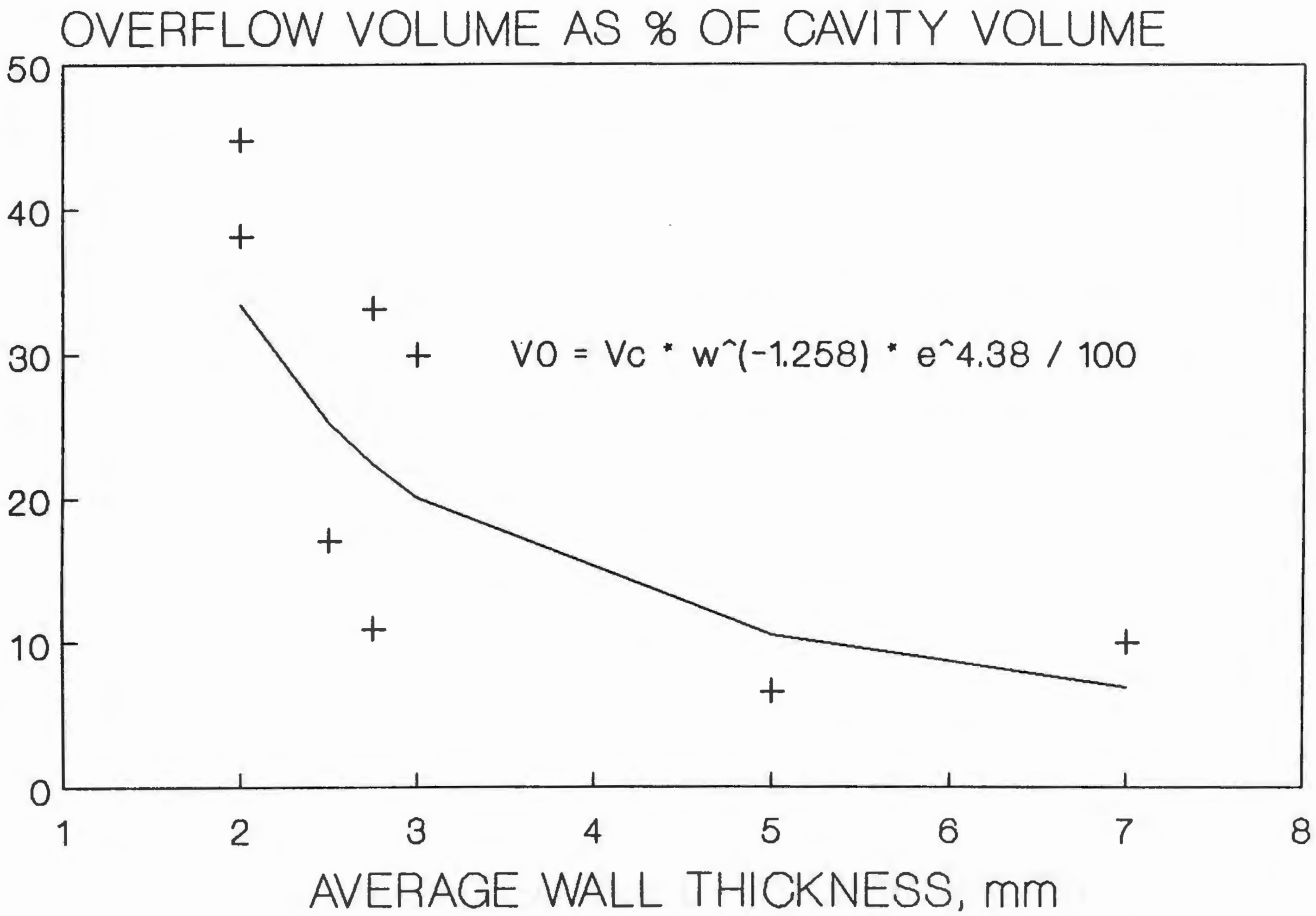

Figure 3.18: **Overflow Well Volume as a Percentage of Cavity Volume, as a Function of Average Wall Thickness**

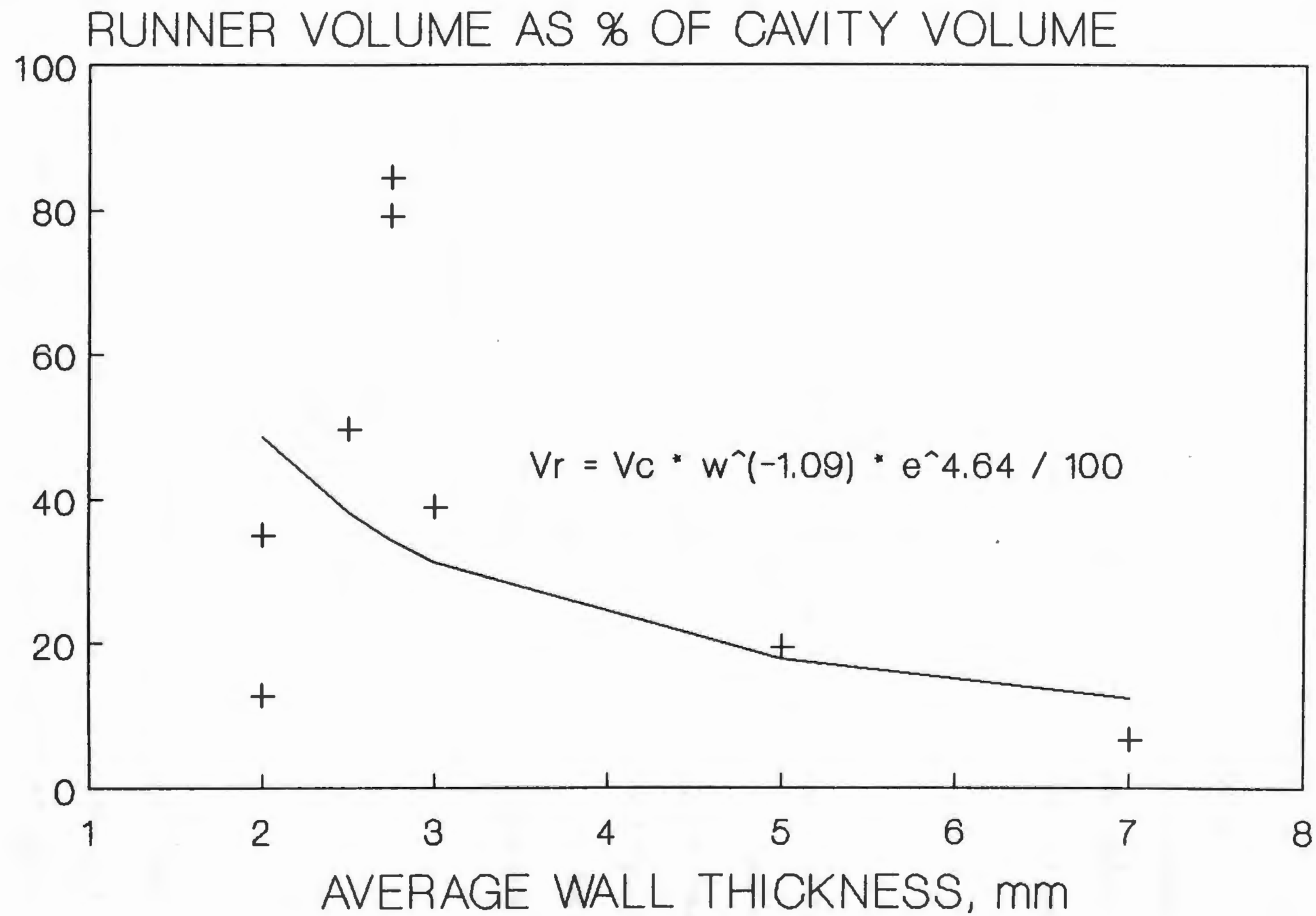

Figure 3.19: Runner Volume as a Percentage of Cavity Volume, as a Function of Average Wall Thickness

usually the same diameter as the plunger tip area, and the thickness of the biscuit, typically about 13 mm. In the hot-chamber process sprues come in a variety of shapes. Data obtained from samples indicates that the average sprue volume is approximately 30,000 mm^2.

Once the shot volume has been calculated, it must be compared with the maximum shot volumes available for the appropriate size machine given in the machine database (Tables 3.2 and 3.3), remembering that for the cold-chamber process, it is usual practice not to exceed 60 percent of the available shot volume.

3.2.2.2 Die Opening Distance

The die opening distance or maximum clamp stroke must next be examined to determine its suitability. The dies must be able to open wide enough so that the part can be ejected from the die without interference (see Fig. 3.20). This required die opening distance, $d_{op(req)}$, can be approximated by the following relationship from work done in the similar process of injection molding [24]:

$$d_{op(req)} = 2 * d_s + 127 ,$$

where: d_s = maximum depth of the shot, mm.

A sample of maximum clamp stroke specifications for various hot and cold-chamber machines is listed in Table 3.4. This data has been analyzed for cold and hot-chamber machines as

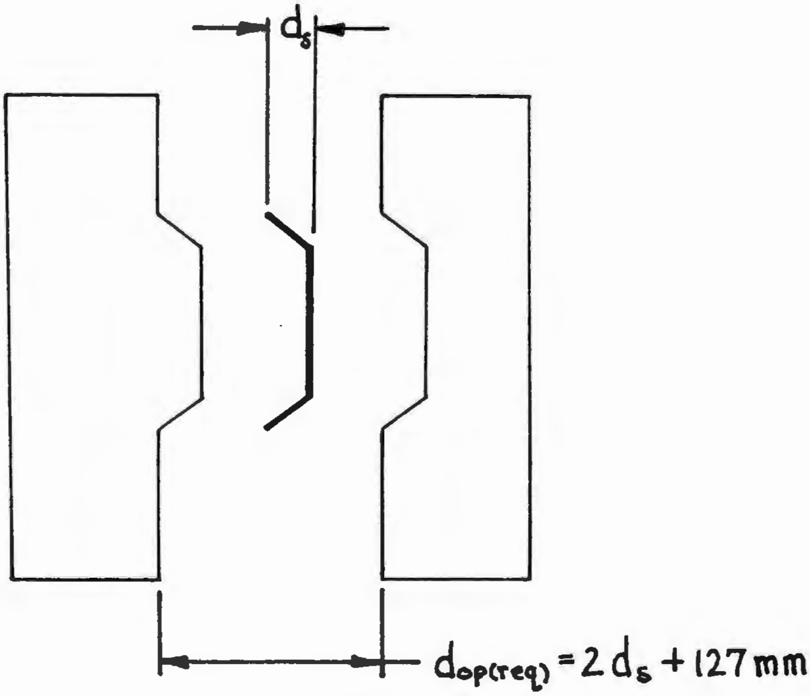

Figure 3.20: Diagram of Die Opening Distance as Related to Depth of Shot

COLD-CHAMBER		HOT-CHAMBER	
CLAMP FORCE (kN)	MAX. CLAMP STROKE (mm)	CLAMP FORCE (kN)	MAX. CLAMP STROKE (mm)
356	152	178	127
577	210	445	152
1335	254	577	210
1780	356	890	203
2225	305	1157	229
2225	267	1335	254
2448	356	1643	254
3560	381	1780	305
4005	381	1780	356
4005	368	2225	305
5340	457	2225	
5340	432	2448	356
6230	457	3560	381
7120	559	4005	381
8010	533	4005	
8010	737	5340	457
8900	533	5340	
8900	686	6230	457
10680	762	7120	
10680	762	8010	533
10680	686	8900	
14240	914	10680	
14240	813		
16020	914		
18690	914		
22250	1067		
26700	1067		

Table 3.4: Clamp Stroke Specifications for Cold and Hot-Chamber Die Casting Machines

shown in Figs. 3.21 and 3.22 , resulting in the following relationships relating maximum available clamp stroke to clamp force:

for cold-chamber machines:

$$d_{op(avail)} = F_c^{0.47} * e^{2.16} , \qquad (3.27)$$

and for hot-chamber machines:

$$d_{op(avail)} = F_c^{0.387} * e^{2.78} . \qquad (3.28)$$

3.2.2.3 Platen Area

The platen area available on the die casting machine must be large enough to contain the area of the entire shot configuration as shown in Fig. 3.23. Chopda [18] found that the necessary platen area, A_{pl}, is related to the projected area of the envelope of the shot as follows:

$$A_{pl} = A_{ps} * 2.9 , \qquad (3.29)$$

where the shot envelope projected area, A_{ps}, is determined by examining the smallest rectangular envelope enclosing all cavities, overflow wells, and the entire feed system as shown in Fig. 3.24. Once calculated, the required platen area must be compared with the available platen area for the machine, shown in Tables 3.5 and 3.6.

COLD-CHAMBER MACHINES

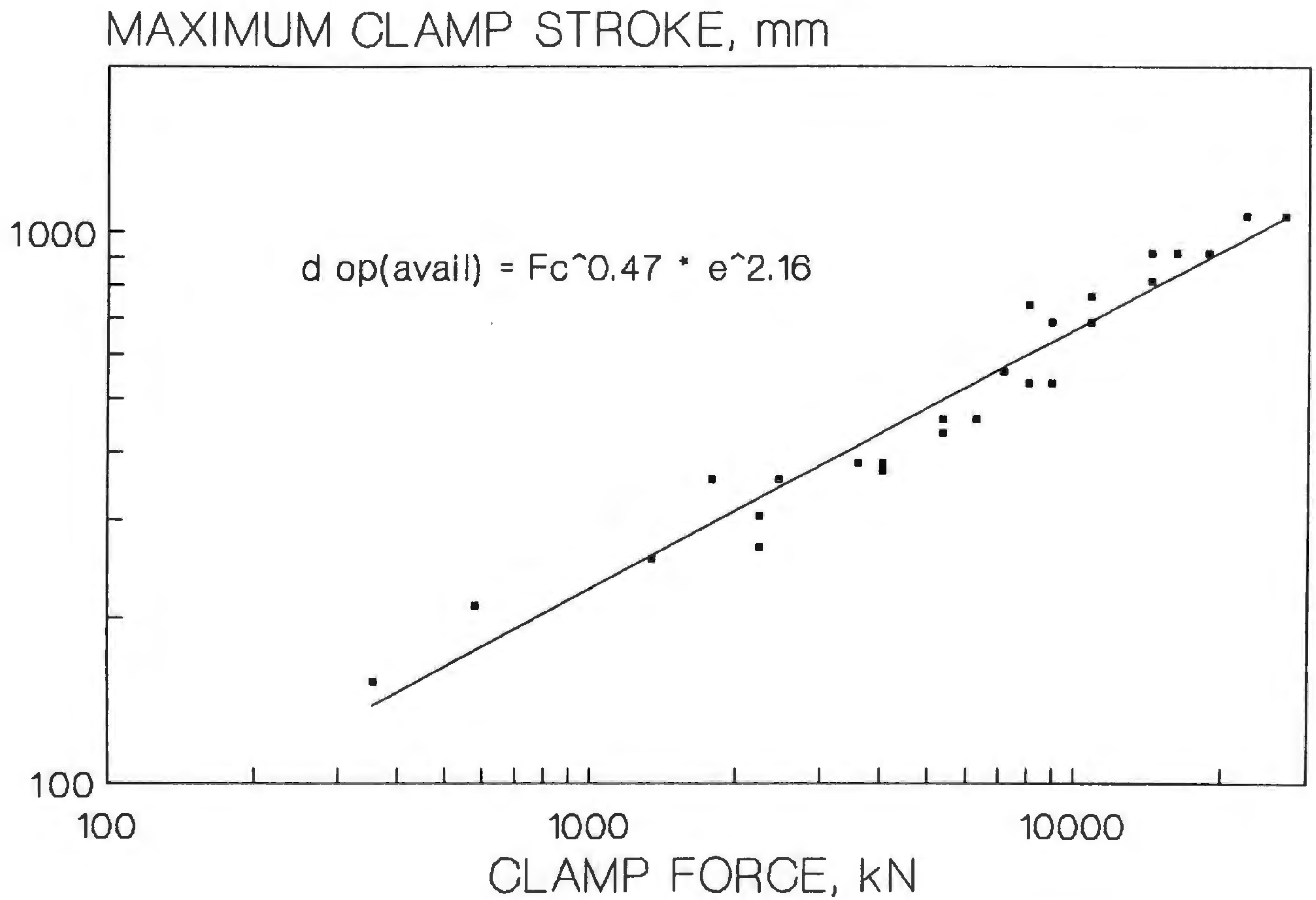

Figure 3.21: Maximum Clamp Stroke as a Function of Clamp Force for Cold-Chamber Machines

HOT-CHAMBER MACHINES

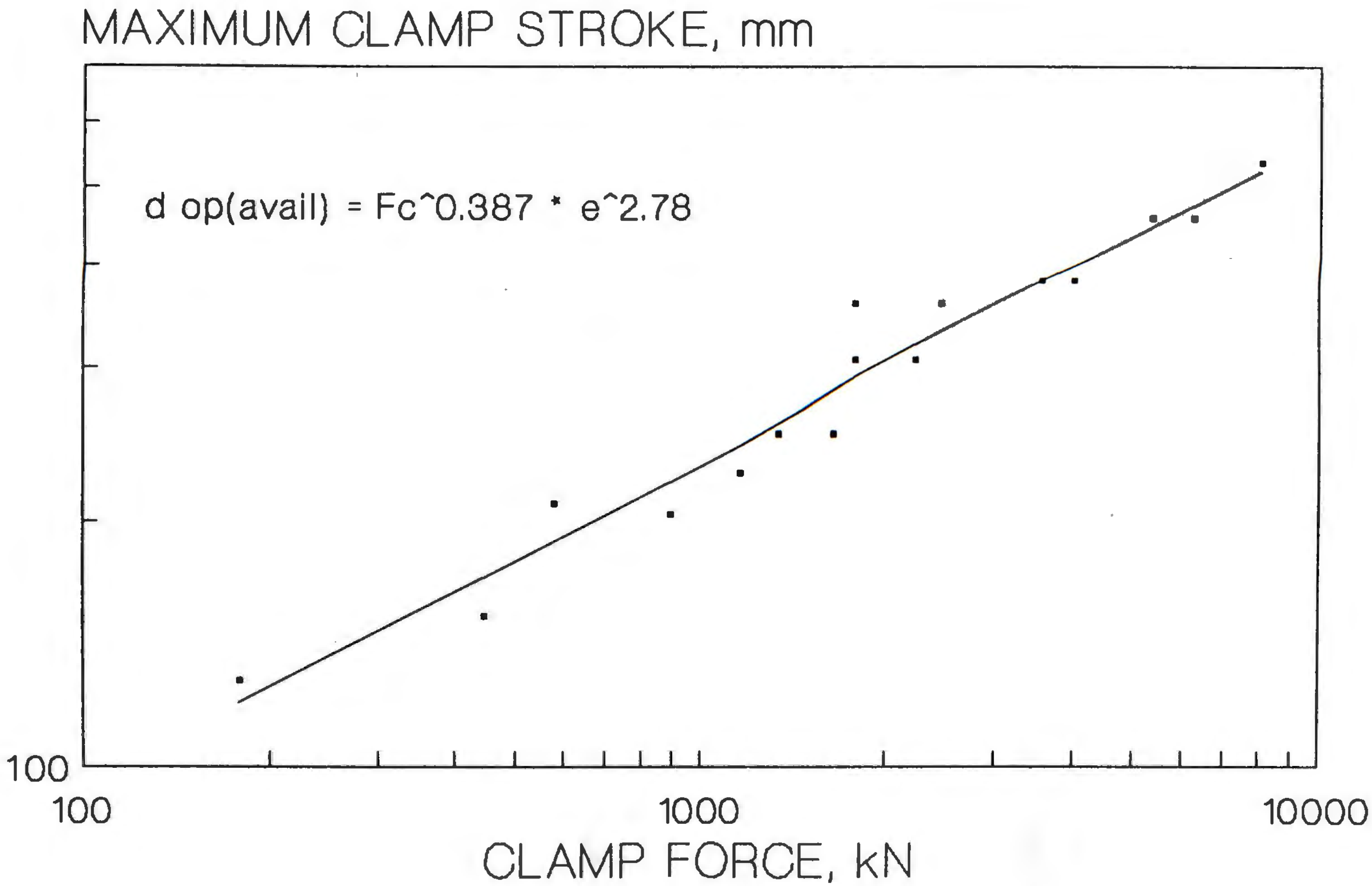

Figure 3.22: Maximum Clamp Stroke as a Function of Clamp Force for Hot-Chamber Machines

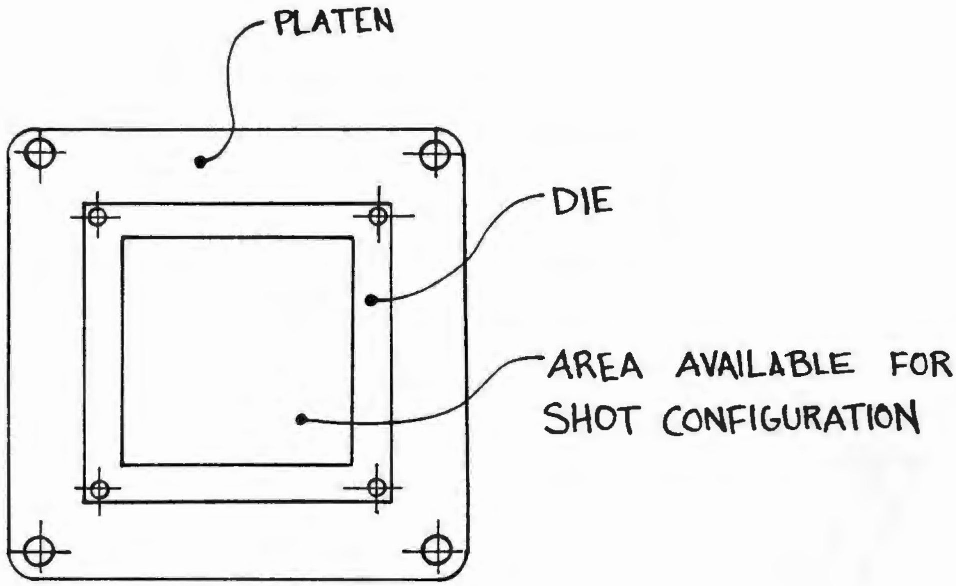

Figure 3.23: Platen Area, Die Area, and Shot Area Configuration

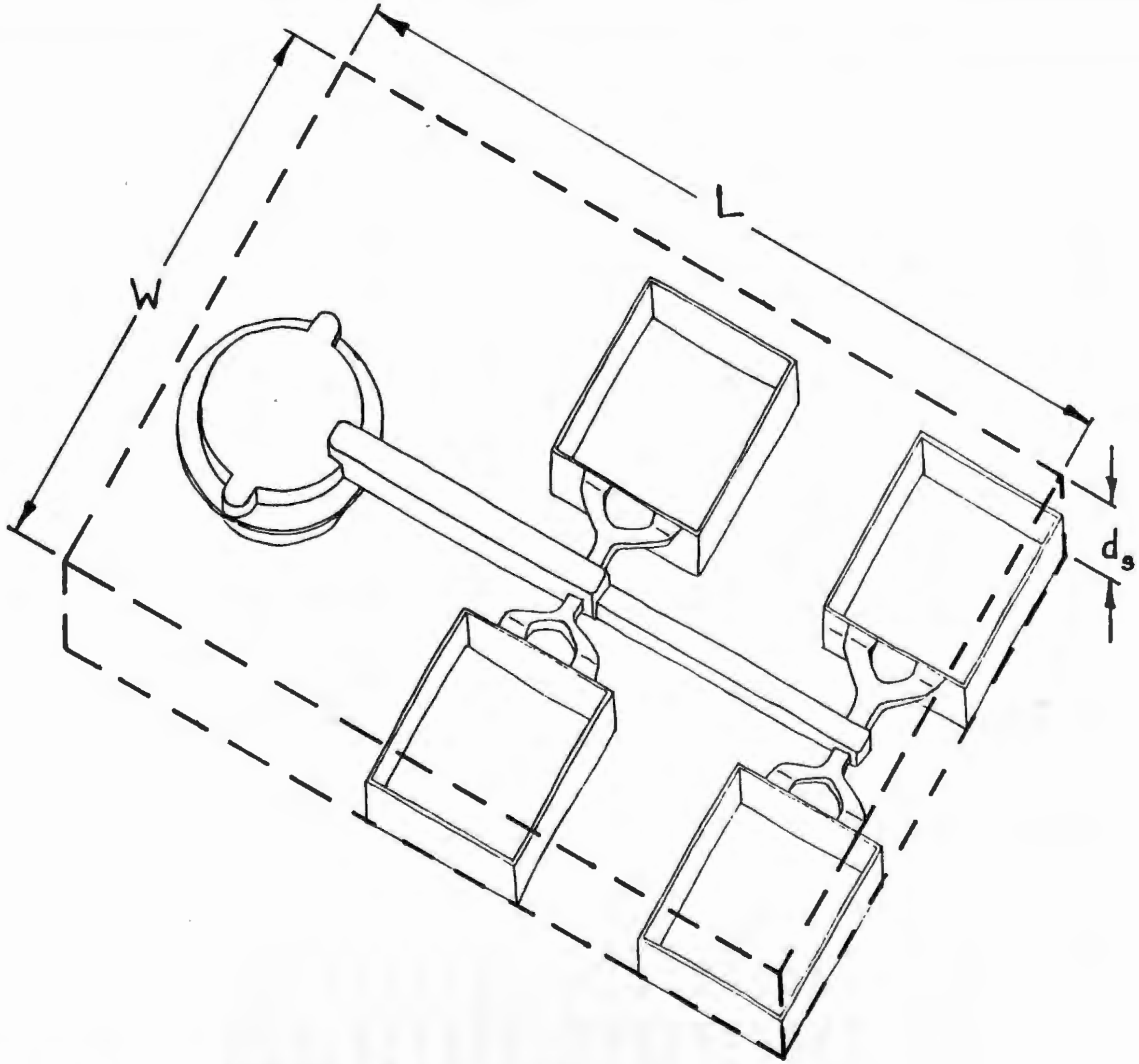

Figure 3.24: Rectangular Shot Envelope

PLATEN DIMENSIONS - COLD-CHAMBER MACHINES

CLAMP FORCE (kN)	STATIONARY PLATEN H (mm)	V (mm)	AREA (mm^2)	MOVING PLATEN H (mm)	V (mm)	AREA (mm^2)
356				348	356	123,742
577	483	641	309,516	483	533	257,419
1335				554	579	320,670
1780	864	909	785,289	864	909	785,289
2225	711	787	559,999	711	762	541,934
2225	864	991	855,482	864	889	767,740
2448				762	800	609,676
3560	991	1087	1,076,901	991	1113	1,102,062
4005	787	984	774,998	838	978	819,676
4005	1067	1219	1,300,643	1067	1092	1,165,159
5340	1219	1384	1,687,739	1219	1219	1,486,449
5340	1295	1473	1,908,383	1295	1346	1,743,867
6230	1016	1238	1,258,062	1016	1200	1,219,352
7120	1524	1778	2,709,672	1524	1524	2,322,576
8010	1270	1441	1,830,642	1270	1270	1,612,900
8010	1549	1715	2,656,446	1549	1549	2,400,640
8900	1270	1441	1,830,642	1270	1270	1,612,900
8900	1727	1981	3,421,929	1727	1727	2,983,220
10680	1600	1651	2,641,930	1651	1651	2,725,801
10680	1753	1969	3,449,993	1753	1753	3,071,607
10680	1778	2032	3,612,896	1778	1778	3,161,284
14240	2261	2261	5,110,312	2261	2261	5,110,312
14240	2438	2108	5,140,635	2108	2108	4,444,507
16020	2210	2464	5,444,505	2210	2210	4,883,216
18690	2261	2261	5,110,312	2261	2261	5,110,312
22250	2540	2718	6,903,212	2540	2540	6,451,600
26700	2337	2413	5,638,698	2337	2337	5,460,634

Table 3.5: Platen Area Specifications for Cold-Chamber Machines

PLATEN DIMENSIONS - HOT-CHAMBER MACHINES

CLAMP FORCE (kN)	STATIONARY PLATEN H (mm)	V (mm)	AREA (mm^2)	MOVING PLATEN H (mm)	V (mm)	AREA (mm^2)
178				348	356	123,742
445				406	381	154,838
577	483	565	272,741	483	483	232,903
890				508	533	270,967
1157	559	635	354,838	559	559	312,257
1335				559	584	326,451
1643	660	711	469,676	660	660	436,128
1780				711	737	523,870
1780	864	909	785,289	864	909	785,289
2225	711	787	559,999	711	787	559,999
2225	864	991	855,482	864	889	767,740
2448				762	800	609,676
3560	991	1087	1,076,901	991	1113	1,102,062
4005	787	984	774,998	838	978	819,676
4005	1067	1219	1,300,643	1067	1092	1,165,159
5340	1219	1384	1,687,739	1219	1219	1,486,449
5340	1295	1473	1,908,383	1295	1346	1,743,867
6230	1016	1238	1,258,062	1016	1200	1,219,352
7120	1524	1778	2,709,672	1524	1524	2,322,576
8010	1270	1441	1,830,642	1270	1270	1,612,900
8900	1727	1981	3,421,929	1727	1753	3,027,091
10680	1778	2032	3,612,896	1778	1778	3,161,284

Table 3.6: Platen Area Specifications for Hot-Chamber Machines

Example:

The machine size is to be estimated for a die casting with the following characteristics:

$w = 2.75$ mm

$A_{pc} = 39{,}115\ mm^2$ (total for six cavities)

$V_c = 214{,}615\ mm^3$ (total for six cavities)

$L = 406$ mm

$W = 368$ mm

$d_s = 33$ mm

The total projected area must first be determined, using Eqns. (3.19) and (3.21).

$A_{po} = 39{,}115 * 2.75^{-0.466} e^{3.76}/100 = 10{,}485\ mm^2$

$A_{pr} = 39{,}115 * 2.75^{-0.376} e^{3.74}/100 = 11{,}275\ mm^2$

From Table 3.1, assume a plunger diameter of 75 mm.

$A_{psb} = \pi/4 * 75^2 = 4{,}418\ mm^2$

Using Eqn. (3.18), the total projected area of the shot can be found.

$A_{pt} = 39{,}115 + 10{,}485 + 11{,}257 + 4{,}418 = 65{,}275\ mm^2$

For Aluminum, $P_m = 89.6$ MPa. Using Eqns. (3.17) and (3.16):

$F_m = 89.6\ MPa * 65{,}275\ mm^2 = 5{,}849\ kN$

$F_c = 5{,}849 / 0.7 = 8{,}355\ kN$

From the machine database, the next largest machine is an 8,900 kN machine with d_{ph} = 229 mm.

Assume P_h = 10.3 MPa.

$A_{plt} = ((10.3 \text{ MPa})*(\pi/4)*(229 \text{ mm})^2)/(89.6 \text{ MPa}) = 4735 \text{ mm}^2$

$d_{plt} = 78 \text{ mm}$

A 78 mm diameter plunger tip is required for a desired metal pressure of 89.6 MPa. Using Eqns. (3.23) and (3.24), the range of plunger tips available for a machine of this size is:

$d_{p(max)} = 8{,}900^{0.369}e^{1.3} = 105 \text{ mm}$

$d_{p(min)} = 8{,}900^{0.361}e^{0.98} = 71 \text{ mm}$

For this machine, the variety of available plunger tip diameters is given in Table 3.1. The next largest plunger from 78 mm is a plunger of tip diameter 83 mm. The required clamp force must now be re-calculated to include the actual plunger tip diameter, as follows:

$A_{pt} = 39{,}115 + 10{,}485 + 11{,}257 + \pi/4 * 83^2 = 66{,}268 \text{ mm}^2$

$F_m = 89.6 * 66{,}268 = 5{,}938 \text{ kN}$

$F_c = 5{,}938 / 0.7 = 8{,}482 \text{ kN} < 8{,}900 \text{ kN}$

The total shot volume must then be determined.

$V_o = 214{,}615 * 2.75^{-1.268}e^{4.38} / 100 = 47{,}511 \text{ mm}^3$

$V_r = 214{,}615 * 2.75^{-1.09}e^{4.64} / 100 = 73{,}776 \text{ mm}^3$

$V_{sb} = \pi/4 * 83^2 * 13 = 70{,}338 \text{ mm}^3$

$V_s = 214,615 + 47,511 + 73,776 + 70,338 = 406,240\ mm^3$

$= 406\ cc$

The shot volume capacity for an 8900 kN machine is 3276 cc. Only 60% of this volume is used, or 1966 cc which is larger than what is necessary, therefore this machine meets the shot volume capacity requirements.

The necessary clamp stroke must then be found.

$d_{op(req)} = 2 * 33 + 127 = 193\ mm$

The available clamp stroke is found next.

$d_{op(avail)} = 8900^{0.47} * e^{2.16} = 623\ mm$

The clamp stroke requirement is met by the clamp stroke specified for the machine.

The necessary platen area must be determined next.

$A_{pl} = 406 * 368 * 2.9 = 433,283\ mm^2$

These requirements are also met because the available platen area given in Table 3.5 is 1,830,642 mm^2 and the horizontal dimensions of the platen are 1270 mm and 1441 mm, respectively, which are greater than the dimensions of the shot envelope.

3.2.3 Summary of Machine Size Estimation

The procedure presented in this section was used to determine the machine size necessary for ten sample parts, namely: five aluminum die castings, produced on cold-chamber machines, and five zinc die castings, produced on hot-chamber machines. In Fig. 3.25, estimated machine sizes,

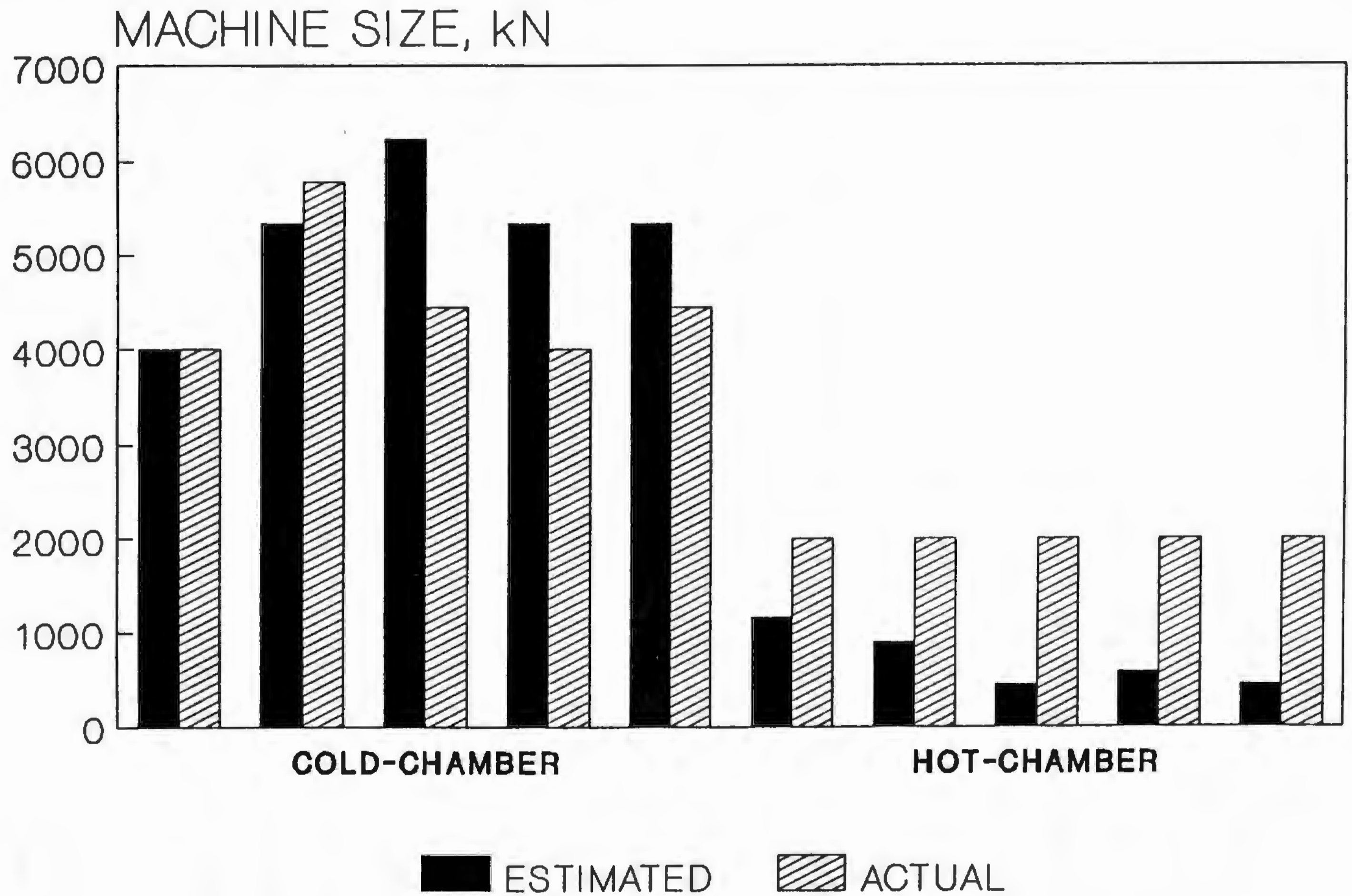

Figure 3.25: Comparison of Estimated and Actual Machine Sizes for Ten Sample Die Castings

using the equations developed in this section, are compared with the actual machines which were used for these parts. The parts used for this comparison were also used to develop the procedures for estimating total projected area, therefore the results of this comparison are solely for the purpose of examining the cavity pressure estimates.

In the case of the parts produced on cold-chamber machines, several machine size estimates are higher than the actual machines used. Discussions with the industrial source indicate that this is due to the limited number of machines possessed by this particular die caster, necessitating the use of machines that are smaller than optimum but which have been adjusted to produce acceptable castings.

In the case of the parts produces on hot-chamber machines, as well as one of the cold-chamber machine parts, the actual machine sizes used were all larger than the estimates. This is due again, to the difference between the database and the actual machines available to the manufacturer. The actual machine size used was, for these cases, the smallest in the factory. Die casting companies with a limited number of machines, will generally not possess very small machines since a larger variety of die cast part sizes can be run on larger machines.

Once the machine size has been determined, the operating rate of the machine and its operator can be found from Fig. 3.1. The cycle time must next be estimated in order to calculate the processing cost.

3.3 Determination of Die Casting Cycle Time

Once the die casting machine size and associated labor rate have been determined, the die casting cycle time can be estimated in order to calculate the die casting processing cost. The die casting process consists of the following cycle time elements:

1. opening and closing the die
2. opening and closing the guard door
3. ladling the molten metal into the shot sleeve (for the cold-chamber process only)
4. filling the molten metal to the gate
5. filling the cavity
6. cooling the casting to solidification
7. ejection of the die casting from the die cavity
8. extraction of the die casting from the ejector pins
9. lubrication of the die

Typical die casting cycles for manual and fully automatic hot and cold-chamber processes are shown in Figs. 3.26 through 3.29. Some of the above operations are performed simultaneously and therefore do not contribute to the total cycle time.

3.3.1 Opening and Closing the Die

Die opening and closing times are a function of the die opening distance, or clamp stroke, of a particular die casting machine. Archer [24] has developed a relationship for die opening and closing times for the injection molding

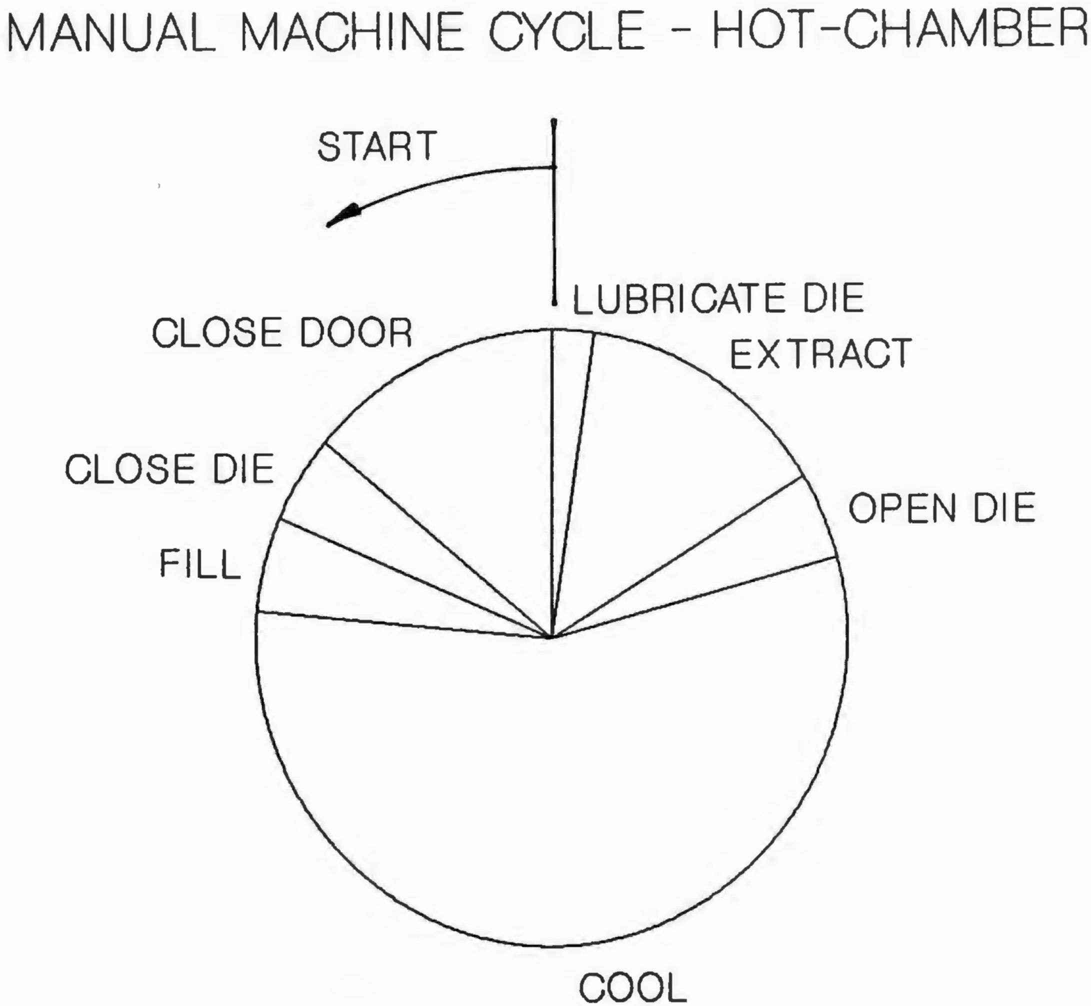

Figure 3.26: Elements of Manual Hot-Chamber Die Casting Machine Cycle

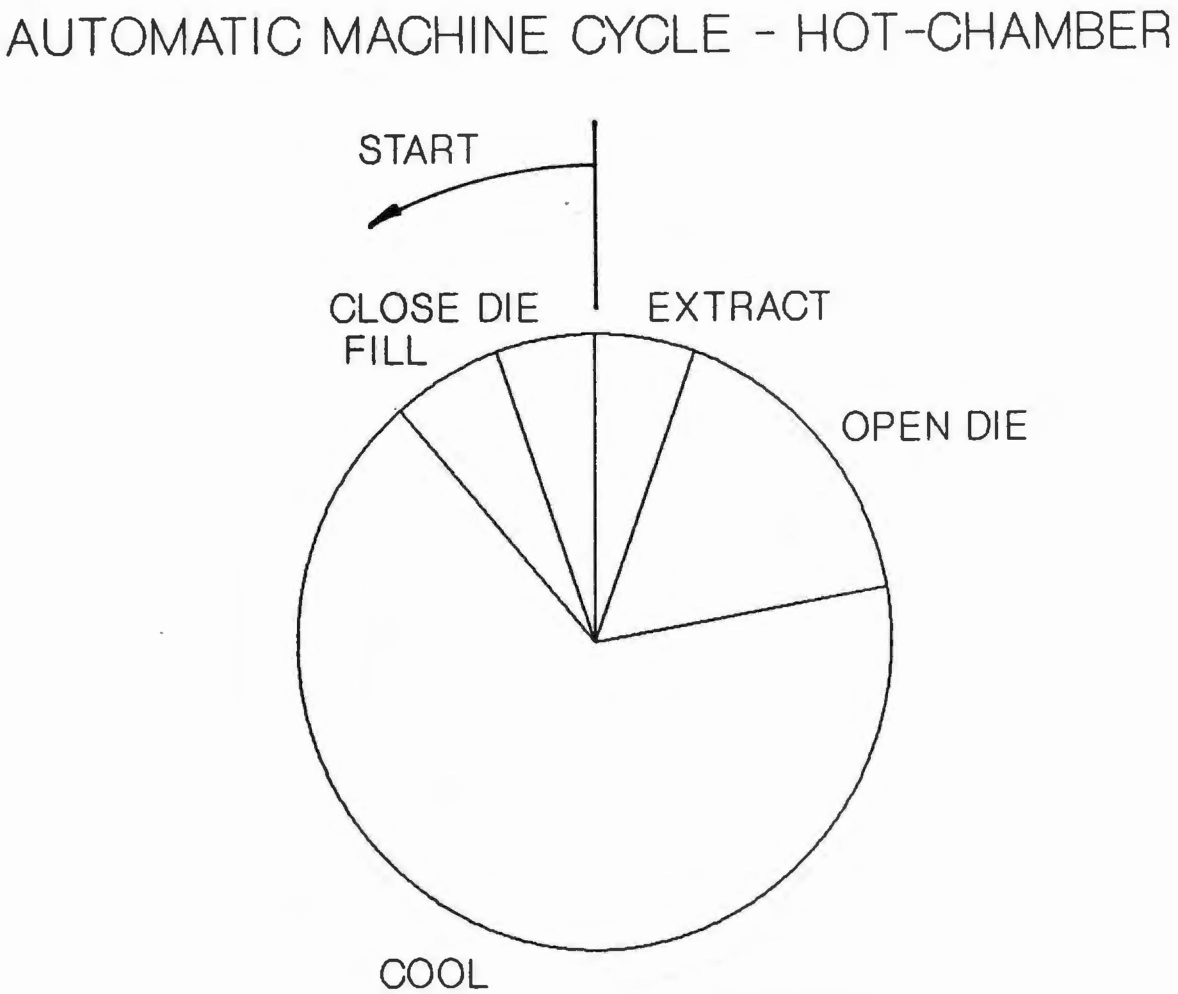

Figure 3.27: Elements of Automatic Hot-Chamber Die Casting Machine Cycle

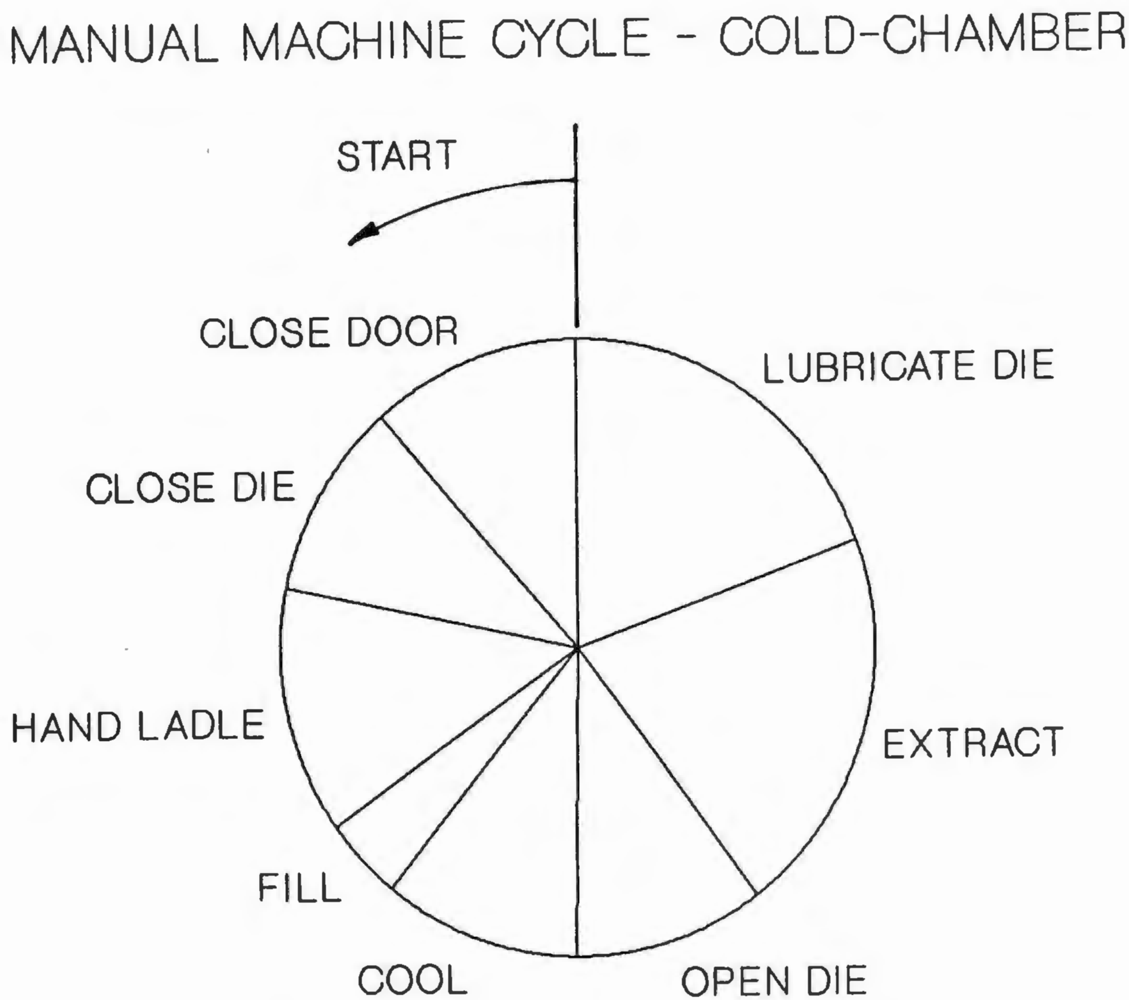

Figure 3.28: Elements of Manual Cold-Chamber Die Casting Machine Cycle

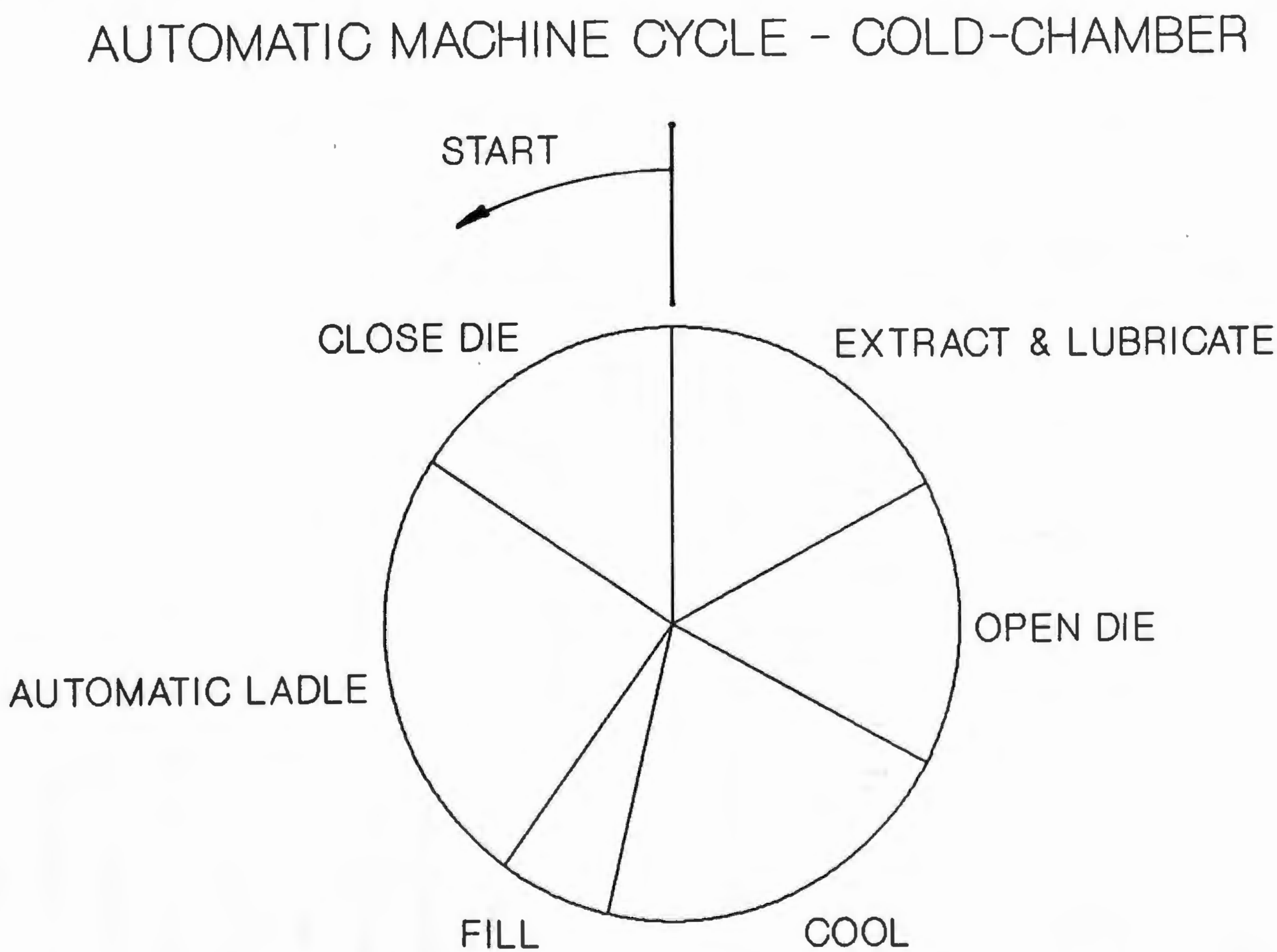

Figure 3.29: Elements of Automatic Cold-Chamber Die Casting Machine Cycle

process which shows this time to be a function of the dry cycle time and the ratio of actual die open distance to specified maximum clamp stroke. This relationship is not valid for the die casting process, as the full machine clamp stroke is commonly utilized in order to facilitate the removal of the casting shot from the ejector pins. For die casting, this means that die opening and closing times are a function of machine clamp stroke, and therefore actually a function of machine clamp force. The following relationship for die opening and closing time was developed from data presented by Ostwald [20] as shown in Fig. 3.30:

$$t_{oc} = 15.2 * e^{(-4101/F_c)} , \qquad (3.30)$$

where: t_{oc} = time for die opening plus closing, s,

and F_c = machine clamp force, kN.

3.3.2 Opening and Closing the Guard Door

Ostwald [20] gives a time of 6 seconds for the time to open and close the guard door on a die casting machine during a manual cycle. Discussion with industrial sources indicates that this is a good estimate. However, as shown in Figs. 3.26 through 3.29, guard door opening does not contribute to the total cycle time. During the manual die casting process, the operator opens the guard door as the die is opening. During the automatic die casting process, the front guard door is constantly in the open position and

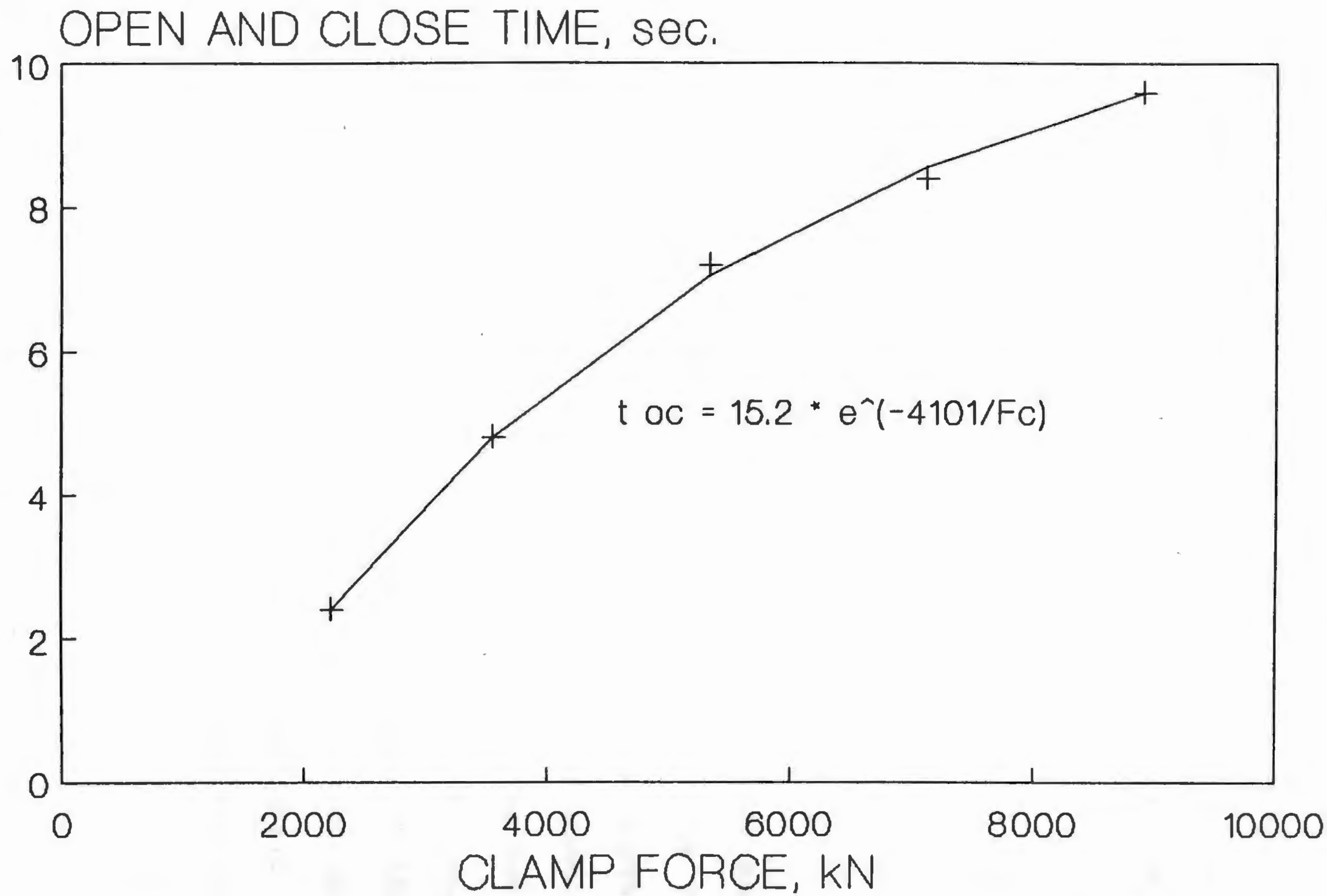

Figure 3.30: Die Opening and Closing Time as a Function of Machine Clamp Force

a guard is provided on the extractor, therefore opening of the guard door does not contribute to the total cycle time.

3.3.3 Ladling the Molten Metal into the Shot Sleeve

The time for manual ladling of aluminum in the cold-chamber process is a function of the volume of molten metal used as described by the following equation that was derived from data presented by Ostwald [20]:

$$t_{lm} = 0.0048 * Vs + 2 , \qquad (3.31)$$

where: t_{lm} = manual ladling time, s, and

V_s = total shot volume, cc.

Automatic ladling equipment takes longer than manual ladling, due to the slower travel of the ladle from the melt container to the shot sleeve, while the pouring appears to take approximately the same amount of time. Discussions with industrial contacts indicates, however, that the travel time does not contribute to the total cycle time. During manual operation, the operator brings the ladle to the pouring hole in the shot sleeve as the die is closing. Similarly, during automatic operation, the automatic ladling device travels to the pouring position during die closing.

3.3.4 Filling the Molten Metal to the Gate

The time to fill the molten metal to the gate can be represented by the distance the plunger travels through the shot cylinder divided by the velocity of the shot plunger, as follows:

$$t_{fs} = l_c/v_p \quad , \tag{3.32}$$

where: t_{fs} = slow shot fill time, s,
l_c = length of shot cylinder, mm, and
v_p = plunger velocity, mm/s.

Typical shot velocities during the slow shot portion of the cycle are estimated to be approximately 190 mm/s [21], and the shot cylinder length is the shot volume capacity divided by the plunger tip diameter.

3.3.5 Filling the Cavity

The cavity fill time is dependent upon the molten metal pressure and the gate area. Gate areas are usually designed to allow sufficient metal through the gate to fill the cavity before premature solidification can take place which would prevent satisfactory cavity filling. Since gate design depends on the dimensional characteristics of the cavity, the filling time can be shown to be related to the wall thickness of the casting. The Society of Die Casting

Engineers [25] developed the following equation for filling time:

$$t_{fc} = 0.035 * ((T_{ir} - T_l + 61)/(T_{ir} - T_{ms})) * w_{ave} \qquad (3.33)$$

where: t_{fc} = cavity fill time, s,

T_{ir} = recommended melt injection temperature, °C,

T_l = liquidus temperature, °C,

T_{ms} = mold surface temperature prior to shot, °C,

and w_{ave} = average wall thickness of die casting, mm.

The recommended processing temperatures are as follows:

for the common Zinc die casting alloy #3:

T_{ir} = 410 °C, T_l = 387 °C, and T_m = 205 °C .

for typical Aluminum die casting alloys:

T_{ir} = 666 °C, T_l = 595 °C, and T_m = 300 °C .

Substitution of these temperatures yields the following simplified equations for cavity fill time, shown in Fig. 3.31:

for Zinc:

$$t_{fc(Zn)} = 0.0143 * w_{ave} , \qquad (3.34)$$

and for Aluminum:

$$t_{fc(Al)} = 0.0126 * w_{ave} . \qquad (3.35)$$

3.3.6 Cooling the Casting to Solidification

A significant portion of the cycle time is the time necessary for the casting to cool until it has solidified

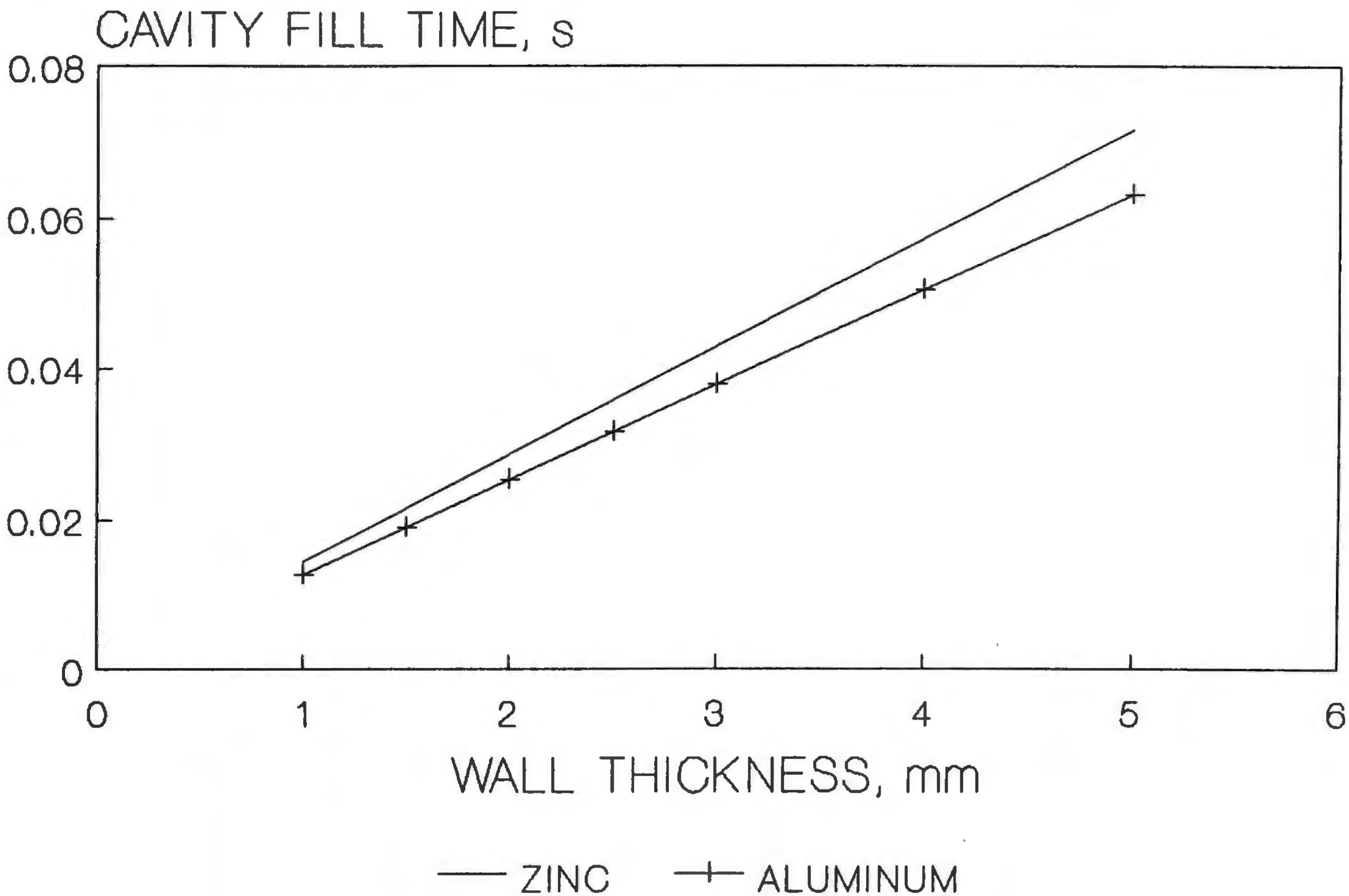

Figure 3.31: Cavity Fill Time as a Function of Casting Wall Thickness

sufficiently so it can be ejected from the die without distortion.

A method has been developed for calculating the cooling time for the similar process of injection molding [26]. This analysis uses the one-dimensional heat conduction equation, assuming that the only significant factor affecting the cooling rate is the thermal resistance of the polymer melt. This is justified because the thermal conductivity of the polymer is orders of magnitude lower than that of the steel mold. In die casting, however, the thermal conductivities of the die casting alloy and the die steel are similar. It has been suggested [27] that in this case the controlling factor is the interfacial resistance between the two metals. This assumption is investigated in the present section.

3.3.6.1 The Cooling Situation in Die Casting

Cooling of the molten metal in the steel die casting mold occurs primarily by means of conduction. Convection is insignificant due to the high conductivities of the metallic melt and mold materials. Radiation is also not a factor once the mold is filled.

The molten metal is injected at a recommended injection temperature, T_{ir}, into a mold of temperature, T_m. The casting then cools to a recommended ejection temperature, T_e.

During solidification, latent heat of fusion is released as the metal crystallizes. This additional heat can be represented by an equivalent increase in temperature, ΔT, given by the following equation [28]:

$$\Delta T = H_f / C_p \ , \tag{3.36}$$

where: H_f = the latent heat of fusion coefficient, kJ/kg,

and C_p = the specific heat of the material, J/kg*°C.

The equivalent injection temperature, T_i, then becomes

$$T_i = T_{ir} + \Delta T \ . \tag{3.37}$$

This approach to the inclusion of heat of fusion in cooling calculations has been used extensively in the literature. The term ΔT is often referred to as "superheat."

The factors contributing to the resistance to thermal conductivity are the thermal resistance of the melt, the thermal resistance of the die, and the thermal resistance of the interface. The temperature distribution across these three regions is illustrated in Fig. 3.32.

Analyses in the following sections will show that the resistance to thermal conductivity of the mold and melt materials is relatively insignificant when compared with the resistance at the interface.

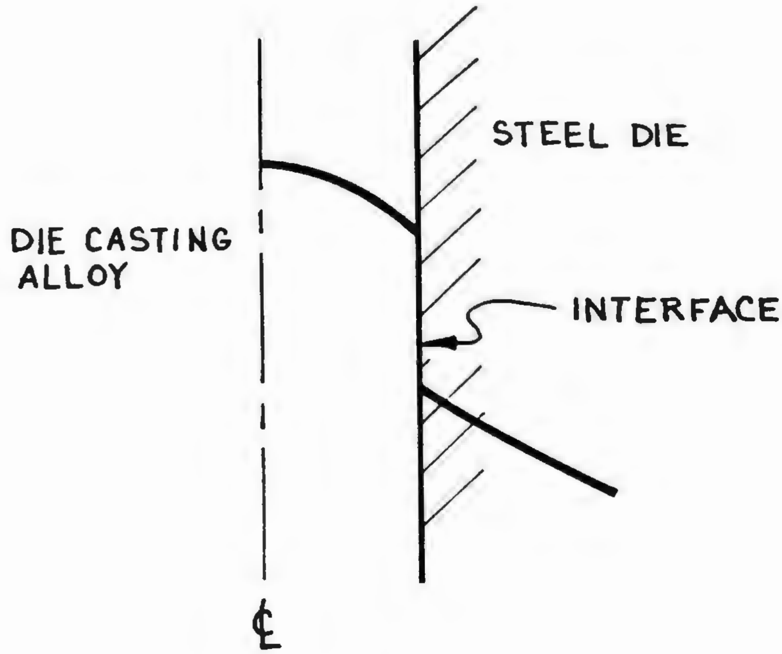

Figure 3.32: Temperature Distribution Across Die Casting Regions and Interface

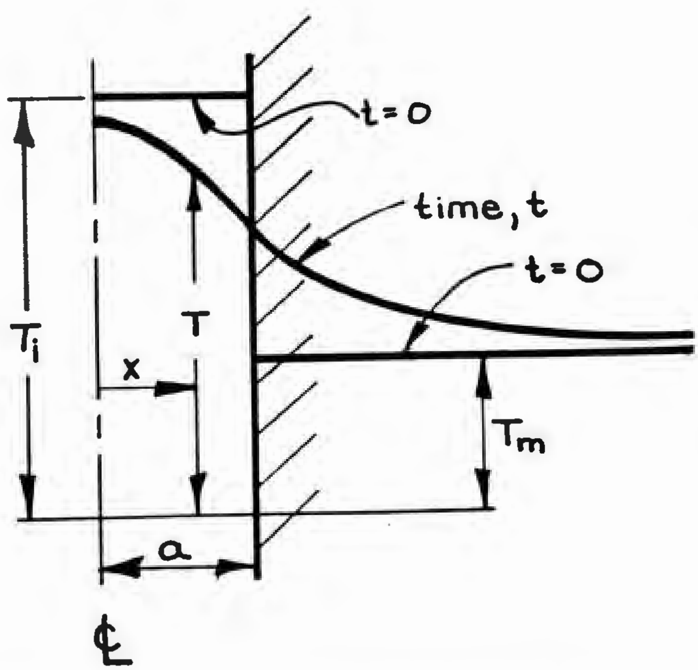

Figure 3.33: Temperature Distribution Neglecting Interface Resistance

3.3.6.2 Thermal Resistance of the Die Material and Melt Material

If it is first assumed that there is no thermal resistance at the interface, an expression for the cooling time, that considers only the thermal resistances of the melt and mold materials, can be derived.

The following analysis considers the flow of heat in a semi-infinite solid bounded by a plane at coordinate position $x=0$, i.e. $0<x<\infty$ (see Fig. 3.33). This applies to the die casting situation where $x=0$ at the centers-plane of the casting wall and the wall thickness is small compared with the thickness of die steel surrounding it. The thermal properties of the materials are assumed to be independent of position and temperature.

It is assumed that initially, when $t=0$, the mold has just been filled. Both the melt and the mold are at temperatures that are constant with respect to position; the melt is at $T=T_i$ and the mold is at $T=T_m$. Immediately, the melt and mold surfaces reach an intermediate temperature. The melt temperature then decreases until T_e, the ejection temperature, is reached at the wall center-plane, and the casting is ejected.

The one-dimensional heat conduction equation is:

$$\frac{\partial^2 T}{\partial x^2} - \frac{1}{\alpha}\frac{\partial T}{\partial t} = 0 , \qquad (3.38)$$

where: T = temperature, °C,

t = time, s, and

α = the thermal diffusivity of the material, mm^2/s.

Thermal diffusivity is, in turn, defined by:

$$\alpha = k/(\rho * C_p) * 1000, \tag{3.39}$$

where: k = the thermal conductivity of the material, W/m*°C,

ρ = density of the material, Mg/m^3, and

C_p = specific heat of the material, J/kg*°C.

The cooling of a semi-infinite solid, where α is constant for all x, and an initial temperature discontinuity exists at x=a, can be described by:

$$\frac{T}{T_0} = \frac{1}{2}\left[\operatorname{erf}\frac{a-x}{2(\alpha t)^{1/2}} + \operatorname{erf}\frac{a+x}{2(\alpha t)^{1/2}}\right] ; \tag{3.40}$$

T_0 is the initial temperature of the region $0<x<a$ and the region $a<x<\infty$ is initially at a temperature $T=0$. The error function, erf, is defined as:

$$\operatorname{erf}(z) = \frac{2}{\pi^{1/2}} \int_0^z e^{-z^2}\, dz . \tag{3.41}$$

It can be readily shown that Eqn. (3.40) satisfies both the one-dimensional heat conduction equation and the initial boundary conditions stated above: see, for example, Carslaw and Jaeger [29].

In the case of die casting, where the region $a<x<\infty$ represents the mold, initially at $T=T_m$, and the region $0<x<a$ is the casting material, initially at $T=T_i$, the cooling equation (3.40) becomes:

$$\frac{T-T_m}{T_i-T_m} = \frac{1}{2}\left[\operatorname{erf}\frac{a-x}{2(\alpha t)^{1/2}} + \operatorname{erf}\frac{a+x}{2(\alpha t)^{1/2}}\right] . \qquad (3.42)$$

In order to find the amount of time elapsed to the point at which the casting is ready for ejection, T_e is substituted for T, at x=0, yielding:

$$T_r = \frac{T_e-T_m}{T_i-T_m} = \operatorname{erf}\left[\frac{a}{2\alpha^{1/2}\ t_c{}^{1/2}}\right] , \qquad (3.43)$$

where T_r is the casting temperature ratio. Inverting Eqn. (3.43) to represent time gives:

$$t_c = \frac{a^2}{4\alpha(\operatorname{erf}^{-1}(T_r))^2} , \qquad (3.44)$$

as the expression for total cooling time.

Equation (3.44) does not represent the true die casting situation in which the thermal diffusivity coefficient of the die casting alloy is different from that of the die steel. The boundary value problem described above, but for which $\alpha_{(0<x<a)}$ is different from $\alpha_{(a<x<\infty)}$, has, however, remained analytically intractable. In the present work, Eqn. (3.44) will be used to establish what may be regarded as upper and lower bound solutions to die casting cooling time, when neglecting interface resistance.

If it is assumed that both materials have the thermal diffusivity of a zinc die casting alloy, then the resulting cooling time will be an underestimate of the actual cooling time. This analysis results in an underestimate of the thermal resistance of the die, because the value of α for zinc is less than the value of α for tool steel. Conversely, if both materials are assumed to have the thermal diffusivity of tool steel, then the analysis will overestimate the cooling time. In this latter case, the thermal resistance of the zinc die casting alloy is overestimated. The range within which the cooling time must exist, neglecting interface resistance, is therefore given by:

$$\alpha_z < \frac{a^2}{4t_c(\mathrm{erf}^{-1}(T_r))^2} < \alpha_s \, , \qquad (3.45)$$

where: α_z = the coefficient of thermal diffusivity for zinc, and

α_s = the coefficient of thermal diffusivity for tool steel.

EXAMPLE

Consider a zinc die casting with a 2.5 mm wall thickness (a=1.25 mm) with the following properties and casting conditions:

$$
\begin{aligned}
H_f &= 113 \text{ kJ/kg} \\
C_p &= 419 \text{ J/kg*°C} \\
\alpha_z &= 40.9 \text{ mm}^2\text{/s} \\
\alpha_s &= 11.5 \text{ mm}^2\text{/s} \\
T_{ir} &= 410 \text{ °C} \\
T_e &= 240 \text{ °C} \\
T_m &= 60 \text{ °C}
\end{aligned}
$$

T_i = 410 °C + (113 kJ/kg)/(419 J/kg*°C) = 680 °C

T_r = (240-60)/(680-60) = 0.29

$erf^{-1}(0.29) \approx 0.25$

$t_{c(Zn)} = ((1.25\text{ mm})^2)/((4)*(40.9\text{mm}^2/s)*(0.25^2)) = 0.15$ s

$t_{c(steel)} = ((1.25\text{ mm})^2)/((4)*(11.5\text{mm}^2/s)*(0.25^2)) = 0.5$ s

Therefore, the actual cooling time, considering only the mold and melt material resistance, lies somewhere between 0.15 s and 0.5 s. Repeating these calculations for a range of wall thicknesses gives the upper and lower bound curves shown in Fig. 3.34.

Typical die casting cooling times [30] are in the order of several seconds rather than fractions of seconds, therefore the interface resistance must be considered.

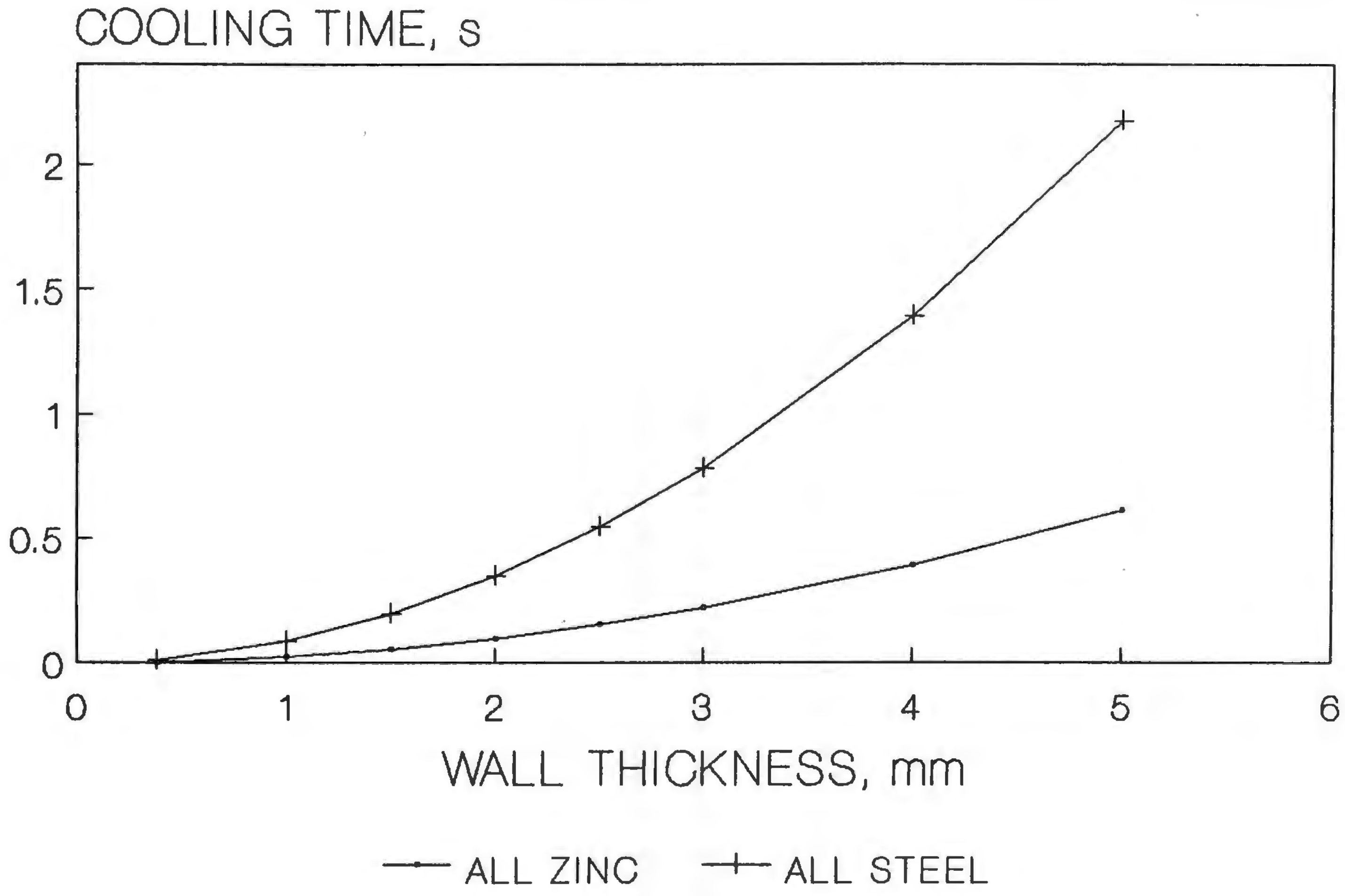

Figure 3.34: Upper and Lower Bound Cooling Times Neglecting Interface Resistance

3.3.6.3 Thermal Resistance at the Interface

If the thermal resistances of the melt and mold materials are neglected, and only the thermal resistance of the interface is considered, the temperature distribution can be represented as shown in Fig. 3.35, where the temperatures of both the mold and the melt are constant with respect to position, x, in each region, at any time, t. The rate of heat flow, dQ/dT, across an area, A, of the interface is [27]:

$$dQ/dT = -hA(T-T_m) \ , \qquad (3.46)$$

where: h = the interface heat transfer coefficient, $kW/m^2 * {}^\circ C$.

The negative sign is needed since positive heat flow is in the direction of decreasing temperature. Since $dQ/dT=mC_p$, and $m=\rho aA$, Eqn. (3.46) becomes:

$$\frac{dT}{dt} \cdot \frac{(\rho aA)C_p}{A} = -h(T-T_m) \ . \qquad (3.47)$$

Integrating this equation gives:

$$\rho a C_p \int_{T_i}^{T} \frac{dT}{T-T_m} = -h \int_0^t dt \ ,$$

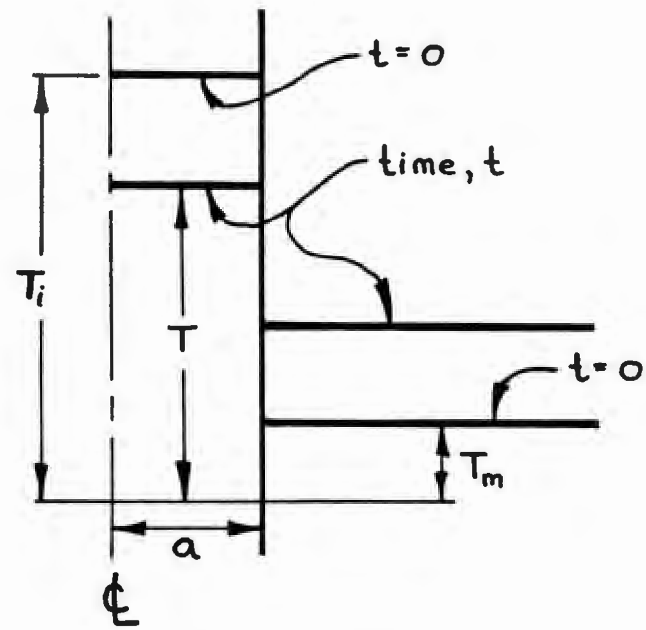

Figure 3.35: Temperature Distribution Considering Only Interface Resistance

$$\rho a C_p \ln\left[\frac{T-T_m}{T_i-T_m}\right] = -ht \ . \tag{3.48}$$

Solving for the cooling time, t_c, using $T=T_e$, results in:

$$t_c = -\frac{\rho a C_p}{h} \ln\left[\frac{T_e-T_m}{T_i-T_m}\right] \ . \tag{3.49}$$

An investigation by Reynolds [31] showed that the value of the interface heat transfer coefficient is governed more strongly by the existence of surface coatings than by the nature of the contacting materials. This is illustrated by the results shown in Fig. 3.36 for casting of lead, aluminum, aluminum/copper alloy, and iron in copper, aluminum and steel molds. The values are given for the mold surfaces in three conditions; namely polished, sand-blasted, and coated with amorphous carbon. It can be seen that the values of the interface heat transfer coefficient, for the most common die casting mold surface of carbon [12], lie in the range of 1.02 to 2.10 $kW/m^2 * {}^\circ C$.

EXAMPLE

Consider a zinc die casting with a 2.5 mm thick wall (a=1.25 mm) with the following properties:

$$\begin{aligned} \rho &= 6.6\ Mg/m^3, \\ C_p &= 418.7\ J/kg * {}^\circ C \\ h &= 1.58\ kW/m^2 * {}^\circ C \\ T_i &= 680\ {}^\circ C \\ T_e &= 240\ {}^\circ C \\ T_m &= 60\ {}^\circ C \end{aligned}$$

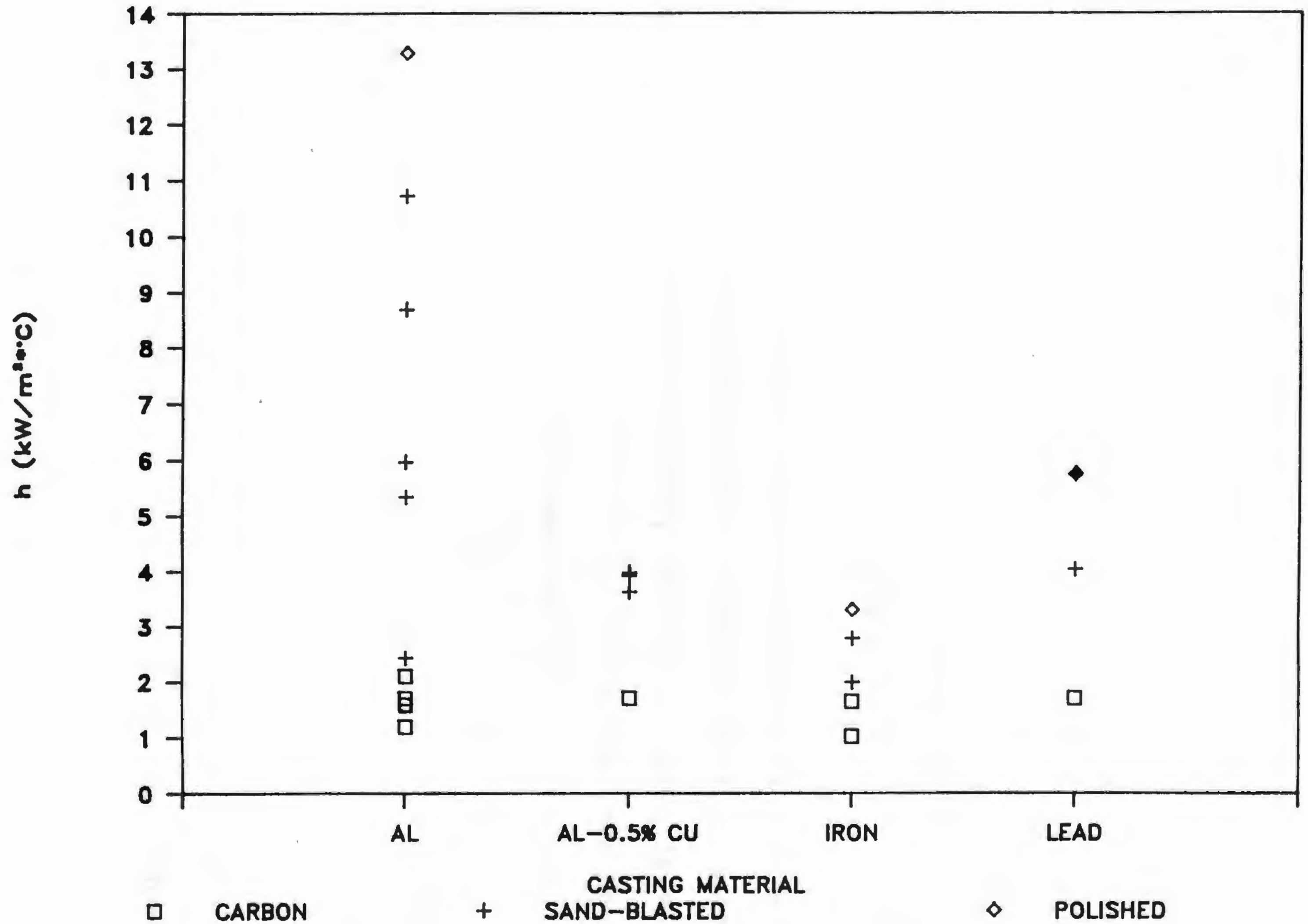

Figure 3.36: Heat Transfer Coefficients Across Casting-Mold Interface for Various Surface Conditions

$$t_c = \frac{-(6.6 \text{ Mg/m}^3)(1.25 \text{ mm})(418.7 \text{ J/kg*°C})}{1.58 \text{ kW/m}^2} * \ln\left[\frac{240-60}{680-60}\right] = 2.7 \text{ s}$$

If cooling times are estimated over a range of wall thicknesses using Eqns. (3.44) and (3.49) with the thermal diffusivity approximated by $\alpha = 1/2(\alpha_s + \alpha_z)$, then the elements of the cooling time are as illustrated in Fig. 3.37. Although these elements that contribute to the cooling time are not additive, this figure shows the importance of the thermal resistance at the interface.

3.3.7 Ejection of the Die Casting From the Die Cavity

Ejection of the part from the cavity usually occurs simultaneously with die opening, unless the part is to be dropped onto a conveyor rather than extracted from the die. The process of dropping die castings rather than extracting them is most common with small zinc castings. Ostwald [20] presents data for this case, which yields the following relationship for part drop time:

$$t_{ej} = 0.0009 * F_c + 1.6 \tag{3.50}$$

where: t_{ej} = time for ejection of die casting during part drop, s, and

F_c = machine clamp force, kN.

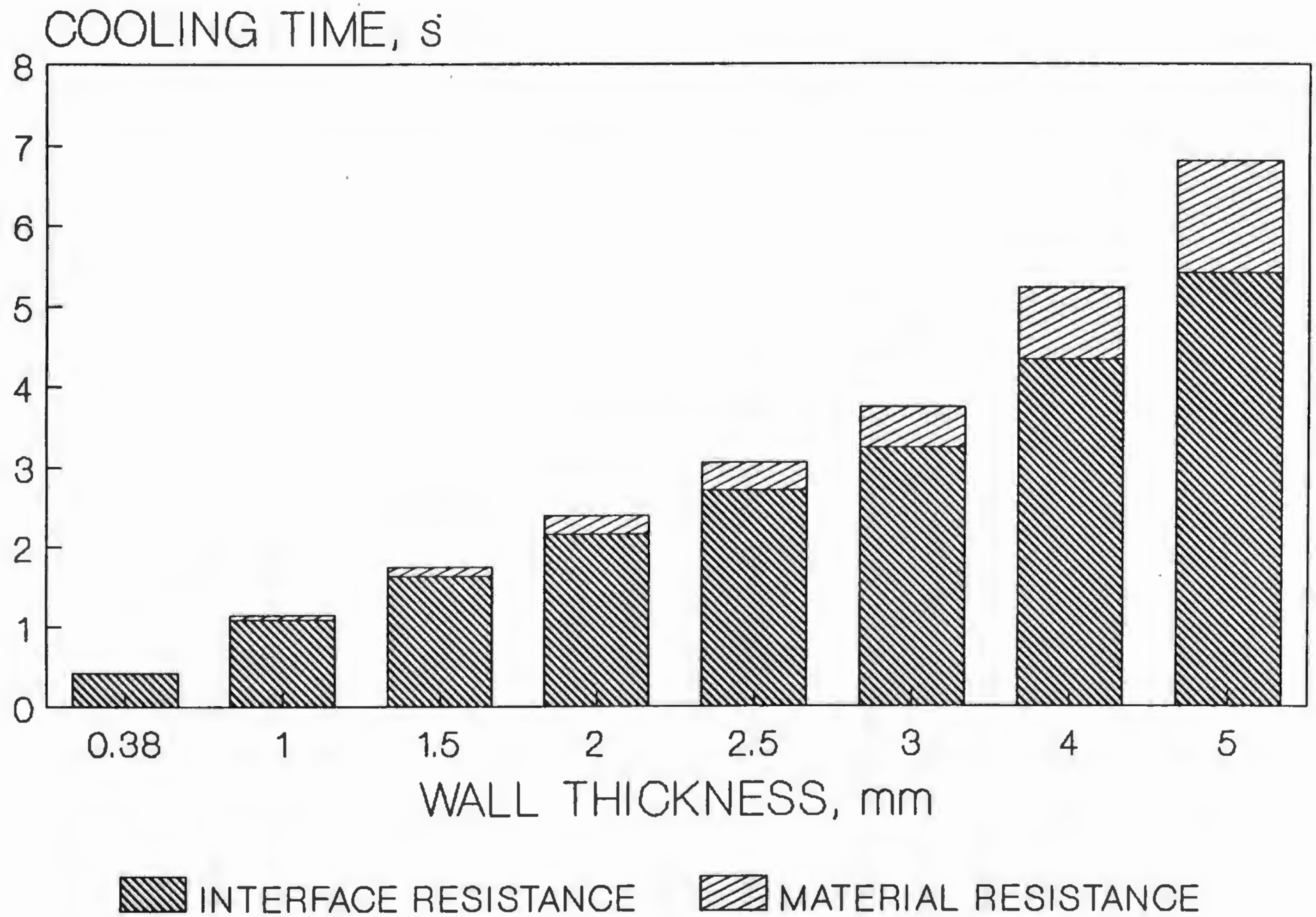

Figure 3.37: Relative Effects of Cooling Time Elements for Zinc Die Castings

3.3.8 Extraction of the Die Casting From the Ejector Pins

Ostwald [20] estimates extraction times to be 3 seconds for Zinc die castings, and 5.4 seconds for Aluminum castings.

3.3.9 Lubrication of the Die

For manual operations, Ostwald [20] estimates the time for lubrication of the die per machine cycle as 0.48 seconds for Zinc, and 5.1 seconds for Aluminum. The time estimates are much greater for Aluminum than for Zinc because lubrication is performed more often and is more critical due to the high temperatures involved in the die casting of Aluminum.

If automatic extraction is used, spray heads are commonly located on the extraction device and lubrication occurs as the extractor is exiting the die casting machine. The time for this operation is therefore included in the time for extraction.

3.3.10 Summary of Cycle Time Estimation

The previous procedure was used to estimate the cycle times for seven sample parts, namely, three zinc die castings and four aluminum die castings. The estimated cycle times are compared with the actual cycle times in Fig. 3.38. This comparison yielded a mean error of -1.7 seconds with a standard deviation of 1.3 seconds.

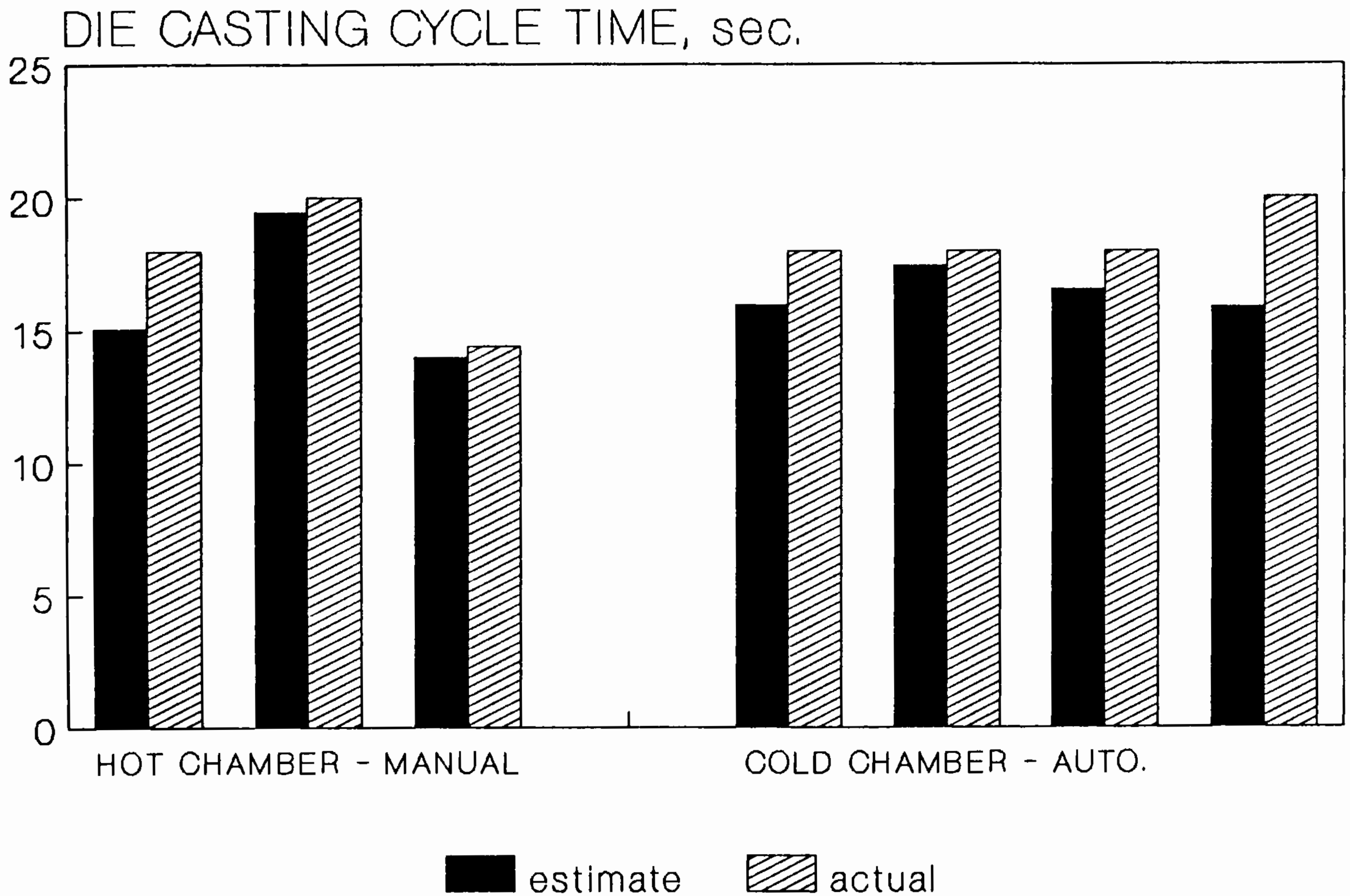

Figure 3.38: Comparison of Estimated and Actual Cycle Times for Seven Sample Die Castings

CHAPTER 4: DIE COST

Discussion with industrial sources indicates that, in general, costs of die casting dies are similar to those of injection molding dies for similarly complex molds. Archer [24] outlines a detailed procedure for the estimation of mold costs for the injection molding process. This procedure was used to estimate the die cost of several die cast samples as shown in Fig. 4.1. The mean error as a percent of the quoted cost for these 14 sample castings is 10.9 percent with a standard deviation of 20.2 percent. It should be recognized that the comparisons in Fig. 4.1 are not with exact or true costs, but with quotations which later become the purchased price. Alternate die quotations from different die makers for the same part often vary by more than the 20 percent deviation between the two sets of values in Fig. 4.1 [24].

Some modifications to this procedure are necessary due to the fact that several factors in the die casting process result in cost differences that may be significant in the estimation of total die cost for some die casting dies. The present chapter will concentrate on factors that influence the cost of die casting dies that differ from those factors already presented in the work on injection molding.

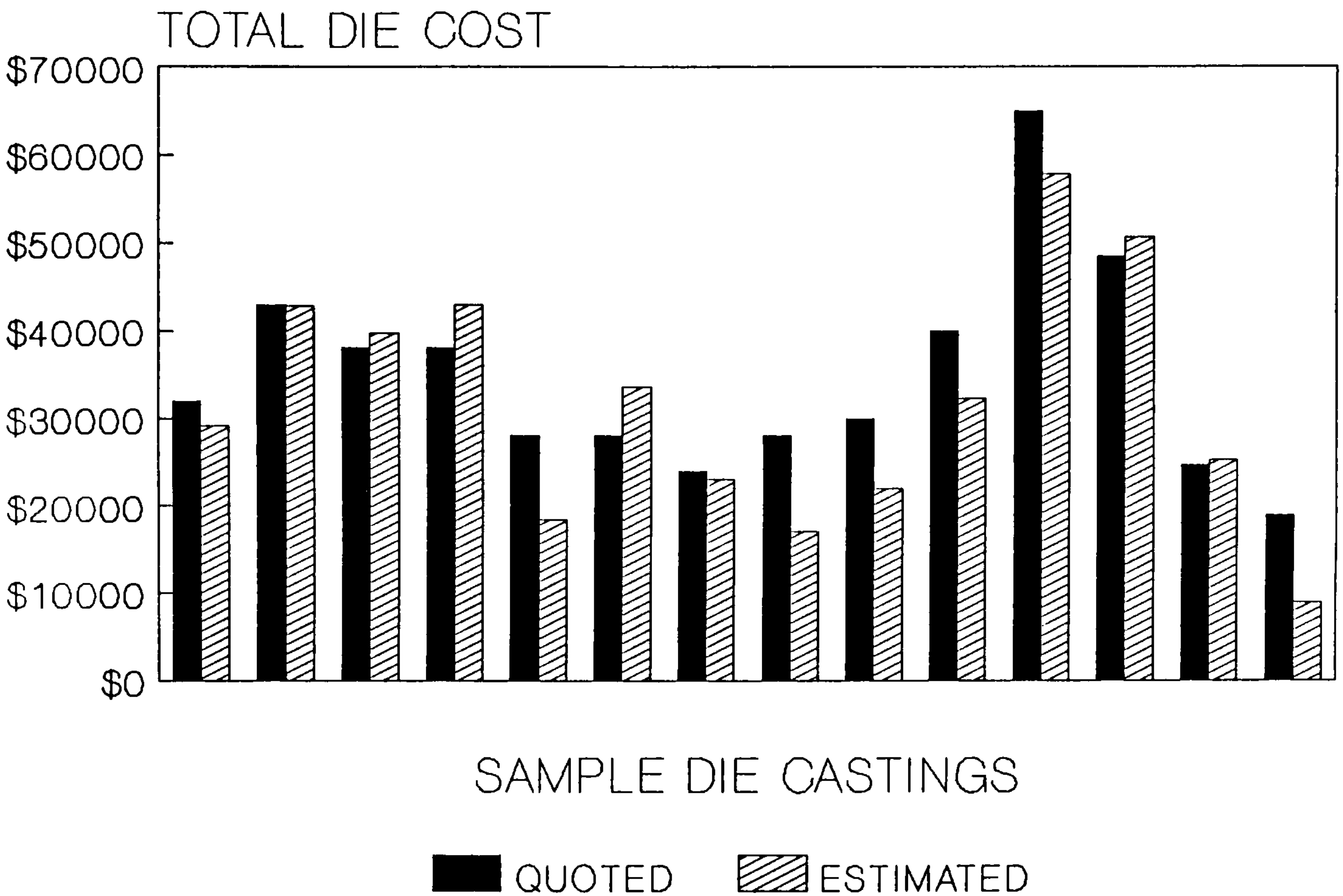

Figure 4.1: Estimates of Die Casting Die Cost Using Injection Molding Cost Estimation Procedure

4.1 Mold Base Cost

As with injection molding, the mold base cost can be divided into the purchased mold base cost and the cost of modifying this mold base to suit a particular die casting task. The purchased price of mold bases are generally higher than injection molding mold bases because larger plate thicknesses are required to prevent heat distortion. In addition, costs of modifying mold bases will be somewhat higher than those of injection molding due to the increased amount of machining required to fabricate larger feed systems.

4.2 Mold Action Cost

The cost estimating procedure for fabricating core pulls and unscrewing devices is the same as that developed by Archer [24].

4.3 Cavity and Core Fabrication Cost

Archer [24] divides the cost of cavity and core fabrication into the following seven elements:

1. projected area
2. part depth
3. tolerance
4. finish
5. type of ejector system
6. shape of parting surface
7. geometric complexity

It appears that the fabrication of die casting cavities and cores are dependent upon the same seven elements and the procedure developed by Archer [24] can be applied directly to die casting.

It should be noted that in the area of surface finish, where Archer [24] gives a rating system of six finishing levels and associated appearance factors for injection molded parts, die castings generally fall into only three surface finish categories [32]. Most die casting cavities, as well as the overflow wells and feed system, require an SPE #3 surface finish which corresponds to a finishing level of 1 and an appearance factor of 1.8 in the injection molding estimating procedure. Most zinc die castings require a higher degree of surface finish, namely SPE #2, which corresponds to a finishing level of 3 and an appearance factor of 2.8. Zinc die castings that are to be chrome plated require an SPE #1 finish, which is a finish level of 4 and an appearance factor of 3.5.

4.4 Summary of Die Cost Estimation

Discussion with some industrial sources indicates that die costs for die casting are generally higher than mold costs for injection molding due to a higher labor rate for die casting toolmaking. However, the industrial samples used in the comparison in this section did not indicate this was the general trend. As with injection molding mold cost estimation, the most accurate die cost estimates can be obtained if toolmaking labor rates appropriate to local tool shops are used in the analysis.

Once the die cost is determined for a particular die casting task, this cost must be divided over the production quantity of the task. Due to the high temperatures involved in the die casting process and the abrasive properties of the molten metals, die life is limited as shown in Fig. 4.2. For this reason, die life must be considered in determining the contribution of die cost to the total part cost, as die replacement is sometimes required before the total production quantity is produced.

Die material	Casting alloy	Component life (no. shots)		Cause of failure (in order of priority)
		Insert	Core	
Mould steel	Lead or tin	5,000,000	5,000,000	Erosion, abrasion (friction and wear)
Mould steel	Zinc	100,000	100,000	Erosion, thermal fatigue, abrasion
BH13	Zinc	5,000,000	1,000,000	Erosion, abrasion, fracture
BH13	Aluminium Magnesium	250,000	100,000	Thermal fatigue, erosion, abrasion, fracture
BH10A, 19, 21	Copper	6,000	2,000	Thermal fatigue, fracture
BH10A, 19, 21	Steel	2,000	1,000	Thermal fatigue, fracture
TZM molybdenum	Copper	30,000	5,000	Fracture, erosion
TZM molybdenum	Steel	10,000	2,000	Fracture, erosion
Tungsten alloy	Copper	50,000	20,000	Fracture
Nimonic	Aluminium Magnesium	250,000	100,000	Erosion, abrasion (wear)
Maraging steel	Aluminium Magnesium	250,000	100,000	Erosion, thermal fatigue, fracture

Figure 4.2: Typical Die Life Estimates for a Variety of Die Materials and Casting Materials (Reprinted from [7])

CHAPTER 5: TRIMMING COSTS

As previously mentioned in the discussion of the determination of optimum number of die cavities, the necessity of the trimming operation in the die casting process is an important factor distinguishing die casting cost estimation from that of injection molding. In the present chapter, the cost of trimming of feed systems, overflow wells, and flash from die cast parts is considered. This cost has been divided into trimming processing cost and the cost of the trimming die.

5.1 Trimming Processing Cost

The trimming processing cost is the product of the trimming time and the hourly operating rate of the machine and operator. As previously mentioned, in section 4.1, the hourly trimming rate can be approximated by a constant value for all machine sizes due to the small tonnages of the machines as well as the relatively small range of machine sizes. As was also previously mentioned, this small machine size means that the hourly rate is dominated by the hourly labor rate of the trim press operator rather than by the cost of the press itself.

5.1.1 Trimming Cycle Time

Trimming cycle times, including the time to load the shot into the press, can be approximated by punch press loading and cycle times, for sheet metalworking, given by Ostwald [20]. These times vary linearly with the sum of the length and width of the part as shown in Fig. 5.1. Trimming cycle time can be represented by the following relationship developed from this data:

$$t_p = (L + W) * 0.012 + 3.6 \ , \qquad (5.1)$$

where: t_p = trimming cycle time, s,

L = length of rectangular shot envelope, mm,

W = width of rectangular shot envelope, mm.

It should be noted that the values of length and width are of the entire rectangular shot envelope rather than of the cavity.

Discussion with industrial sources indicates that actual trimming times tend to approach die casting machine cycle times. This is due in part to longer loading times of die casting shots over sheet metal loading times. Die casting shots are oddly shaped and are therefore more difficult to align in the die. Additional time is also required for periodic cleaning of the trimming die, as flash and other scrap create a build-up of debris. Since the casting and trimming of a given batch of die castings is done at the same time, the cycle time of the die casting

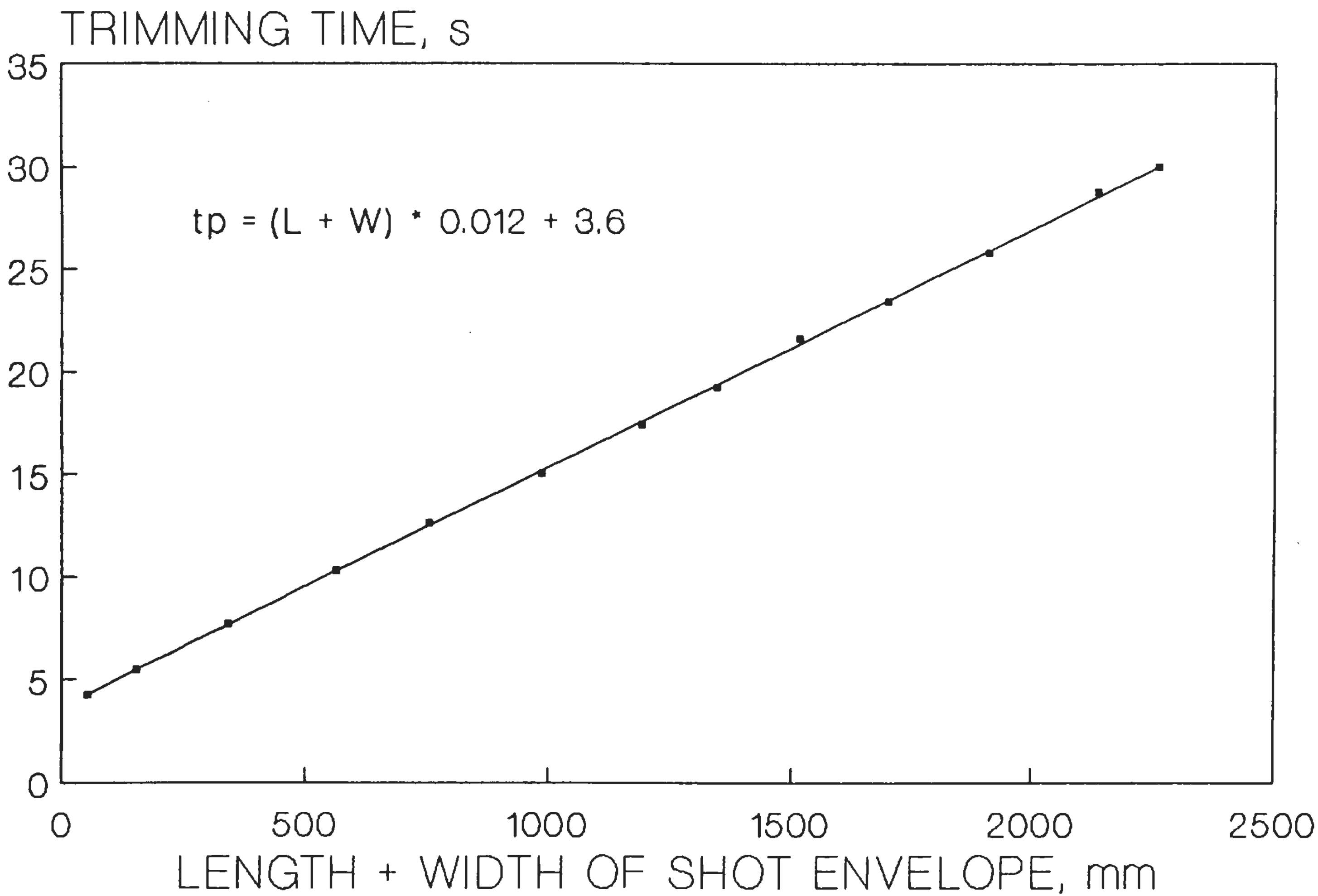

Figure 5.1: Trimming Cycle Time as a Function of Shot Envelope Dimensions

machine determines the time the trimming press is in operation. The die casting machine cycle time can be multiplied by a trimming machine operating rate. If an additional operator is needed to run the trim press, this machine rate may include the labor rate of this operator. Otherwise, the operator's labor rate is included in the die casting machine operating rate and only the basic rate for the trimming machine needs to be applied.

5.2 Trimming Die Cost

Trimming die costs can be approximated by sheet metal punching die costs. A procedure was developed by Zenger [33] that divides the total sheet metal punching die cost into the following contributing elements:

1. punch area
2. standard punches
3. custom punches
4. die set

Zenger [33] developed a point system which results in the following equation for total punching die cost, or in the case of the present analysis, total trim die cost:

$$DC = ((PAP + SPP + CPP) * MPV) + CDS \quad , \qquad (5.2)$$

where: DC = total trimming die cost, \$,

PAP = punch area points,

SPP = standard punch points,

CPP = custom punch points,

MVP = manufacturing point value,

CDS = cost of the die set, \$.

For die casting trim dies, the number of punch area points, PAP, as given by Zenger [33], is related to the rectangular die casting shot envelope as follows:

$$PAP = 0.00031 * A_{ps} + 23 \quad (5.3)$$

where: A_{ps} = projected area of rectangular shot envelope, mm^2.

Standard punch points, SPP can be determined separately for both round and non-round standard punches with the following equation [33]:

$$SPP = K * 2 * NUM_{sp} + 0.4 * NUM_{dsp} \quad (5.4)$$

where: NUM_{sp} = total number of standard punches,

NUM_{dsp} = number of different standard punches,

and: $K = 1$ for round punches, and

$K = 1.75$ for non-round punches.

Custom punch points, CPP, can be determined by the following relationship [33]:

$$CPP = 3 * NUM_{cp} + (8 + (0.05906 * P_{cp})) \ , \qquad (5.5)$$

where: NUM_{cp} = number of custom punches,

P_{cp} = total periphery of custom punches, mm.

Finally, the cost of the die set, CDS, is related to the die casting shot envelope as follows [33]:

$$CDS = 120 + A_{ps} * 0.00377 \ . \qquad (5.7)$$

The manufacturing point value corresponds directly to the hourly rate for trim die manufacture. Discussion with industrial sources indicates that $35/hour is a reasonable approximation for this parameter.

The preceding procedure was used to estimate the trim die costs of 13 sample parts. A comparison of these estimates with quoted trim die costs is shown in Fig. 5.2. The estimation procedure, when compared with the quoted trim die costs, resulted in a mean error of -3.4 percent with a standard deviation of 31 percent. A review of the test cases showed no apparent reason for the fairly poor comparison of test cases 4, 6, and 11. Clearly, more comparisons will be needed to refine the above equations.

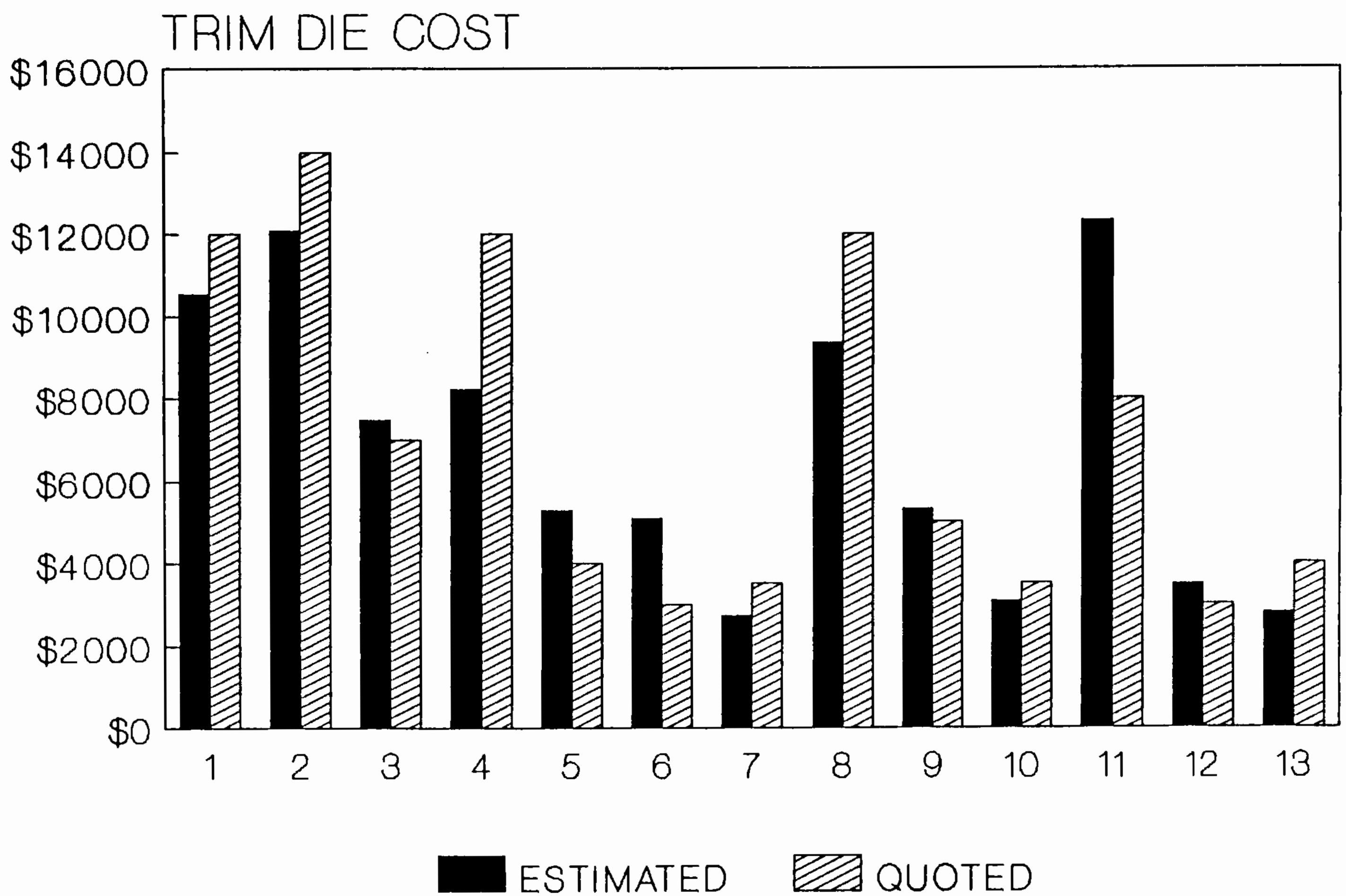

Figure 5.2: Comparison of Estimated and Quoted Trim Die Costs

CHAPTER 6: CONCLUSIONS

In this project, an early cost estimation methodology for die cast components has been developed. This methodology is intended for use in the early stages of design and therefore requires only the input of parameters that are readily available to the designer at this concept design stage, such as the type of material and the geometric characteristics of the component,.

The methodology consists of the following:

a. a method for the determination of optimum number of die cavities
b. a method for the selection of appropriate machine size
c. a method for the determination of cycle time
d. a method for determination of casting die costs
e. a method for determination of trimming die costs
f. a die casting database consisting of the following:
    1. machine specifications
    2. processing information
    3. material properties

The methodology was developed with the considerable use of samples, quotes,and other information that was obtainable only through industrial contacts.

The methodology presented here can be further expanded to include the cost of die cast components of magnesium and copper-based alloys. This will require additional data collection from industrial sources that produce these types of castings. Further industrial information collection will also allow the methodology presented here to be refined and will allow expansion of the database.

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APPENDIX: DIE CASTING ALLOY PROPERTIES DATABASE

A. Physical Properties

PHYSICAL PROPERTIES OF DIE CASTING ALLOYS

alloy name commercial (ANSI) [ASTM] {UNS} <SAE>	density Mg/m^3	therm. cond'y W/m*C	spec. heat cap. J/kg*C	thermal diff'y mm^2/s	latent heat of fusion kJ/kg	solidus temp. degrees C	liquidus temp. degrees C	coeff. of thermal expansion 10^-6 m/m*C	electrical conduct'y %	electical resist'y 10^-9 ohm m
ALUMINUM										
A13 (A413.0) [S12B] {A14130} <305>	2.66 (1)	121 (1) b	963 (1)	47.289	389 (1)	574 (4)	582 (2)	20.4 e 21.4 h 22.4 i (1)	31 (1) j	55.6 (1) a
413 (413.0) [S12B] {A04130}	2.66 (1)	121 (1) b	963 (1)	47.289	389 (1)			20.4 e 21.4 h 22.4 i (1)	31 (1) j	55.6 (1) a
A380 (A380.0) [SC84A] {A13800} <306>	2.74 (1)	96.2 (1) b	963 (1) c	36.458	389 (1)	540 (1)	595 (1)	21.8 (1) h	27 (1) j	75 (1) a
380 (380.0) [SC84B] {A03800} <308>	2.74 (1)	96.2 (1) b	963 (1) c	36.458	389 (1)	540 (1)	595 (1)	22 (1) h	27 (1) j	75 (1) a
A360 (A360.0) [SG100A] {A13600} <309>	2.63 (1)	113 (1) b	963 (1) c	44.616	389 (1)	555 (1)	595 (1)	21 e 22 h 23 i (1)	30 (1) j	61 (1) a
360 (360.0) [SG100B] {A03600}	2.63 (1)	113 (1) b	963 (1) c	44.616	389 (1)	555 (1)	595 (1)	21 e 22 h 23 i (1)	28 (1) j	61 (1) a
384 (384.0) [SC113A] {A03840} <303>	2.82 (1)	92 (1)				515 (1)	580 (1)	20.8 (1)	22 (1) j	
A384.0	2.77 (1)	96 (1)				515 (1)	580 (1)	20.7 (1)	23 (1) j	

PHYSICAL PROPERTIES OF DIE CASTING ALLOYS, CONT'D.

alloy name commercial (ANSI) [ASTM] {UNS} <SAE>	density Mg/m^3	therm. cond'y W/m*C	spec. heat cap. J/kg*C	thermal diff'y mm^2/s	latent heat of fusion kJ/kg	solidus temp. degrees C	liquidus temp. degrees C	coeff. of thermal expansion 10^-6 m/m*C	electrical conduct'y %	electical resist'y 10^-9 ohm m
ALUMINUM										
390	2.73 (1)	134 (1)				505 (1)	650 (1)	18 (1) e	27 g 25 k (1)	
218 (518.0) [G8A] {A05180}	2.57 (1)	96.2 (1)				535 (1)	620 (1)	24.1 (1) e	25 (1) j	
383 (383.0) [SC102A] {A03830}	2.74 (1)	96.2 (1)				515 (1)	580 (1)	21.1 (1) e	23 (1) j	
43 (C443.0) [S5C] {A34430} <304>	2.69 (1)	142 (1)	963 (1) c	54.816	389 (1)	575 (1)	630 (1)	22 e 23 h 24 i (1)	37 (1) j	46.6 (1) a
Almag35 (535.0) [GM70B] {A0350}	2.62 (1)					550 (1)	630 (1)	21.6 l 23.6 e 25.6 h 26.6 i (1)	23.2 (1) j	44.7 (1) a
A218 A535.0 {A15350}	2.62 (1)					550 (1)	630 (1)	21.6 l 23.6 e 25.6 h 26.6 i (1)	23.2 (1) j	44.7 (1) a
B218 B535.0 {A25350}	2.62 (1)					550 (1)	630 (1)	21.6 l 23.6 e 25.6 h 26.6 i (1)	23.2 (1) j	44.7 (1) a

PHYSICAL PROPERTIES OF DIE CASTING ALLOYS, CONT'D.

alloy name commercial (ANSI) [ASTM] {UNS} <SAE>	density Mg/m^3	therm. cond'y W/m*C	spec. heat cap. J/kg*C	thermal diff'y mm^2/s	latent heat of fusion kJ/kg	solidus temp. degrees C	liquidus temp. degrees C	coeff. of thermal expansion 10^-6 m/m*C	electrical conduct'y %	electical resist'y 10^-9 ohm m
ZINC										
Zamak 3 Alloy 3 [AG40A] {Z33520} {L14400} <903>	6.60 (1)	113 (1) d	418.7 (1) e	40.891	113 (19) m	381 (1)	387 (1)	27.4 (1) e	27 (1) j	63.694 (1) a
Zamak 5 Alloy 5 [AC41A] {Z35530} {L14100} <925>	6.60 (1)	108.9 (1) d	418.7 (1) e	39.407		380 (1)	386 (1)	27.4 (1) e	26 (1) j	65.359 (1) a
Alloy 7 <903>	6.60 (7)	113 (7)	418.7 (7)	40.891		381 (7)	387 (7)	27.4 (7)	27 (7) j	63.694 (7) a
Alloy 16 ILZRO 16	7.10 (7)	104.7 (7)	402 (7)	36.682 (7)		415 (1) 416 (7)	417 (1) 418 (7)	27 (7) n		84 (1) a
ZA										
ZA-8 {Z35630}	6.30 (7)	115 (7)	435 (7)	41.963		375 (7)	404 (7)	23.2 (7)	27.7 (7)	
ZA-12 {Z35840}	6.03 (1)	116 (7)	450 (7)	42.749		380 (1) 377 (7)	432 (1) 432 (7)	28 (1) e	25 (1) j 28.3 (7)	
ZA-27 {Z25630}	5.01 (1)	122.5 (7)	525 (7)	46.573		375 (7) 378 (1)	487 (7) 492 (1)	26 (7)	29.7 (7) 28 (1) j	

PHYSICAL PROPERTIES OF DIE CASTING ALLOYS, CONT'D.

alloy name commercial (ANSI) [ASTM] {UNS} <SAE>	density Mg/m^3	therm. cond'y W/m*C	spec. heat cap. J/kg*C	thermal diff'y mm^2/s	latent heat of fusion kJ/kg	solidus temp. degrees C	liquidus temp. degrees C	coeff. of thermal expansion 10^-6 m/m*C	electrical conduct'y %	electical resist'y 10^-9 ohm m
MAGNESIUM										
[AZ91A] {M11910} <501>	1.81 (1)	72 (1) f	1050 (1) a	37.884	373 (1)	470 (1)	595 (1)	26 (1) e	10.1 (1) g,j	170 (1) g
[AM60A] {M10600} <501A>	1.79 (1)	61 (1) a				540 (1)	615 (1)	25.6 (1) e		
[AS41A] {M10410}	1.77 (1)	68 (1) a	1020 (1) a	37.664		565 (1)	620 (1)	26.1 (1) e		
[AZ91B] {M11912} <501A>	1.81 (1)	72 (1) f	1050 (1) a	37.884	373 (1)	470 (1)	595 (1)	26 (1) e		
COPPER										
Silicon brass 879 [ZS331A] {C87900}	8.50 (5)		377 (5)		pure CU 212 206	899 (5)	927 (5)		15 (5) j	
Silicon brass 878 [ZS133A] {C87800}	8.28 (1)	28 (1) a	375 (1) a	9.0177		821 (1)	917 (1)	19.6 (1) p	6.7 (1) j	284 (1) a
Manganese Bronze865 [B147-8A] {C86500}	8.3 (1)	87 (1) a	373 (1) a	28.101		862 (1)	880 (1)	21.6 (1) q	20.5 (1) j 22 (5) j	

PHYSICAL PROPERTIES OF DIE CASTING ALLOYS, CONT'D.

alloy name commercial (ANSI) [ASTM] {UNS} <SAE>	density Mg/m^3	therm. cond'y W/m*C	spec. heat cap. J/kg*C	thermal diff'y mm^2/s	latent heat of fusion kJ/kg	solidus temp. degrees C	liquidus temp. degrees C	coeff. of thermal expansion 10^-6 m/m*C	electrical conduct'y %	electical resist'y 10^-9 ohm m
COPPER										
Manganese Bronze862 [B147-8B] {C86200}	7.9 (1)	35 (1) a	376 (1) a	11.782		899 (1)	941 (1)	22 (1) p	7.5 (1) j	
Yellow brass 858 [Z30A] {C85800}	8.41 (1)	83.9 (1) a	376 (1) a	26.532		903 (1) 871 (5)	920 (1) 899 (5)	20.2 (1) e	19.6 (1) j	
Bronwite	8.0 (5)					818 (5)	843 (5)		2 (5) j	
OM metal	8.5 (5)					875 (5)	890 (5)			
A metal			376 (5)			854 (5)	904 (5)			
White Tombasil	8.2 (5)					871 (5)	898 (5)		3 (5) j	

KEY TO NOTES ON PHYSICAL PROPERTIES

a. @ 20 degrees C
b. @ 25 degrees C
c. @ 100 degrees C
d. @ 70-140 degrees C
e. @ 20-100 degrees C
f. @ 100-300 degrees C
g. F temper
h. @ 20-200 degrees C
i. @ 20-300 degrees C
j. % IACS @ 20 degrees C, volumetric
k. T5 temper
l. @ -60-20 degrees C
m. pure Zn
n. estimated
p. @ 20-260 degrees C
q. @ 21-93 degrees C

B. Mechanical Properties

MECHANICAL PROPERTIES OF DIE CASTING ALLOYS

alloy name commercial (ANSI) [ASTM] {UNS} <SAE>	ultimate tensile strength MPa	tensile yield strength q MPa	elongation % in 50mm	shear strength MPa	hardness	fatigue strength MPa	elastic modulus x GPa	compressive yield strength MPa	Poisson's ratio	impact strength J
ALUMINUM										
A13 (A413.0) [S12B] {A14130} <305>	290 (1) b	130 (1) b	3.5 (1) b	170 (1) 131 (16) d	80 Bhn (16) c,d	130 (1) b 71 (15) d,f	71 (6) b		0.33 (6)	2.7 (6) b
413 (413.0) [S12B] {A04130}	300 (1) b	140 (1) b 145 (6) b	2.5 (1) b	170 (1)	120 Bhn (17) c,h	130 (1) b	71 (17) h			
A380 (A380.0) [SC84A] {A13800} <306>	325 (1) b	160 (1) b	3.5 (1)	185 (1) 207 (16) d	80 Bhn (16) c,d	138 (1) b	71 (1) 26.5 (1) g		0.33 (1)	4.7 (6) b
380 (380.0) [SC84B] {A03800} <308>	315 (1) b 324 (16)a,d	160 (1) b 165 (16)a,d	3.5 (1)	195 (1) 200 (16) d	80 Bhn (16) c,d	138 (1) b 131 (15) d,f	71 (1) 26.5 (1) g		0.33 (1)	4.1 (15) n
A360 (A360.0) [SG100A] {A13600} <309>	320 (1) b	170 (1) b 165 (16)a,d	3.5 (1) b 5 (16) d	180 (1) 200 (16) d	75 Bhn (16) c,d	120 (1)	71 (1) 26.5 (1) g		0.33 (1)	5.7 (6) b
360 (360.0) [SG100B] {A03600}	305 (1) b 324 (16)a,d	170 (1) b	2.5 (1) 3.0 (16) d	190 (1) 207 (16) d	75 Bhn (16) c,d	140 (1) 131 (15) d,f	71 (1) 26.5 (1) g		0.33 (1)	
384 (384.0) [SC113A] {A03840} <303>	330 (1) b 324 (16)a,d	165 (1) b 172 (16)a,d	2.5 (1)	200 (1) b 207 (16) d	85 Bhn (1)	140 (1) 131 (15) d,f	71 (16) d		0.33 (6)	2.7 (6) b
A384.0	330 (1) b	165 (1) b	2.5 (1)	193 (4)	85 Bhn (1)					

MECHANICAL PROPERTIES OF DIE CASTING ALLOYS, CONT'D.

alloy name commercial (ANSI) [ASTM] {UNS} <SAE>	ultimate tensile strength MPa	tensile yield strength q MPa	elongation % in 50mm	shear strength MPa	hardness	fatigue strength MPa	elastic modulus x GPa	compressive yield strength MPa	Poisson's ratio	impact strength J
ALUMINUM										
390	280 (1) b,d 295 (1) b,e	240 (1) b,d 260 (1) b,e	<1.0 (16) d		120 Bhn (16) c,d	138 (15) d,f	82 (16) d			
218 (518.0) [G8A] {A05180}	310 (1) d	190 (1) d	8.0 (16) d 5 (6) b	200 (15) d	80 Bhn (16) c,d 65 Bhn (6) b,c	138 (15) d,f	71 (6) b		0.33 (6)	11.2 (6) b
383 (383.0) [SC102A] {A03830}	310 (1) b	150 (1) b	3.5 (1)		75 Bhn (1)	145 (1)	71 (17) h		0.33 (1)	4 (1)
43 (C443.0) [S5C] {A34430} <304>	230 (1) b,d	110 (1) b,d 96 (16)a,d	9.0 (16) d	145 (1) 131 (16) d	65 Bhn (1) 50 Bhn (16) c,d	115 (1)	71 (1) 26.5 (1) g		0.33 (1)	6.1 (6) b
Almag35 (535.0) [GM70B] {A05350}	275 (1) b,d, e	140 (1) b,d, e								
A218 A535.0 {A15350}										
B218 B535.0 {A25350}										

MECHANICAL PROPERTIES OF DIE CASTING ALLOYS, CONT'D.

alloy name commercial (ANSI) [ASTM] {UNS} <SAE>	ultimate tensile strength MPa	tensile yield strength q MPa	elongation % in 50mm	shear strength MPa	hardness	fatigue strength MPa	elastic modulus x GPa	compressive yield strength MPa	Poisson's ratio	impact strength J
ZINC										
Zamak 3 Alloy 3 [AG40A] {Z33520} {L14400} <903>	283 (1) a	221 (22) h	10 (1)	214 (1)	82 Bhn (1) c	48 (15)	655 (6) i	414 (15)		58 (1) m
Zamak 5 Alloy 5 [AC41A] {Z35530} {L14100} <925>	328 (1) a	269 (17) h	7 (1)	262 (1)	91 Bhn (1) c	56 (1) k	724 (6) i	600 (15)		65 (1)
Zamak 7 Alloy 7 <903>	283 (15)		13 (15)	214 (18)	80 Bhn (15)	47 (18)		414 (18) v		58 (15) m
Alloy 16 ILZRO 16	225-235 (1)	135-145 (1)	5-6 (1)		75-77 Bhn (1) c		97 (1)			
ZA										
ZA-8 {Z35630}	365-386 (16)	283-296 (16)	6-10 (15)	276 (3)	85-90 Bhn (15) 99-107 Bhn (16) c	103 (3) f	86 (17) h	255 (3)		33-47 (16) l
ZA-12 {Z35840}	359 (15) 393-414 (16)	262 (15) 310-331 (16)	1-3 (15) 4-7 (16)	296 (3)	100-115 Bhn (15) 95-105 Bhn (16) c		83 (17) h	269 (3)		27-50 (16) l 20-37 (16) h
ZA-27 {Z25630}	407-441 (16)	359-379 (16)	1-3 (15) 2-3.5 (16)	324 (3)	105-120 Bhn (15) 116-122 Bhn (16) c	145 (3) f	78 (17) h	358 (3)		9.5-16 (16) l

MECHANICAL PROPERTIES OF DIE CASTING ALLOYS, CONT'D.

alloy name commercial (ANSI) [ASTM] {UNS} <SAE>	ultimate tensile strength MPa	tensile yield strength q MPa	elongation % in 50mm	shear strength MPa	hardness	fatigue strength MPa	elastic modulus x GPa	compressive yield strength MPa	Poisson's ratio	impact strength J
MAGNESIUM										
[AZ91A] {M11910} <501>	230 (1) d	150 (1) d 159 (6) b	3 (1) d	140 (1) d	63 Bhn 75 Re (1) d	97 (1) d,f	45 (1) d 17 (1) d,g	165 (1) d 152 (6) b	0.35 (1) d	2.7 (1) d,n
[AZ91B] {M11912} <501A>	230 (1) d	150 (1) d 159 (15)	3 (1) d	140 (1) d	63 Bhn 75 Re (1) d	97 (1) d,f	45 (1) d 17 (1) d,g	165 (1) d 152 (6) b	0.35 (1) d	2.7 (1) d,n 4 (15) n
AZ91D	y	y	y	y	y	y	y	y	y	y
[AM60A] {M10600} <501A>	220 (1) d	130 (1) d	6 (1) d				45 (1) d	130 (1) d	0.35 (1) d	
[AS41A] {M10410}	210 (1) d	140 (1) d 152 (6) b	6 (1) d 4 (6) b				45 (1) d	140 (1) d 117 (6) b	0.35 (1) d	
COPPER										
Silicon brass 879 [ZS331A] {C87900}	483 (5)	241 (5)	25 (5)		70 Rb (5) 120 Bhn (6) b,c		103 (5)			68 (5) t
Silicon brass 878 [ZS133A] {C87800}	585 (1) b	310 (1) b,p 345 (5)	25 (1) b		163 Bhn (1) 85 Rb (5)	150 (1) o	138 (1)	183 (1) v 515 (1) w		95 (5) t 43 (1) n
Manganese Bronze865 [B147-8A] {C86500}	490 (5)	193 (5)	30 (5)		100 Bhn (5) r 130 Bhn (5) s	145 (1) k	103 (5)	165 (1) v 240 (1) j 545 (1) w		43 (1) n

MECHANICAL PROPERTIES OF DIE CASTING ALLOYS, CONT'D.

alloy name commercial (ANSI) [ASTM] {UNS} <SAE>	ultimate tensile strength MPa	tensile yield strength q MPa	elongation % in 50mm	shear strength MPa	hardness	fatigue strength MPa	elastic modulus x GPa	compressive yield strength MPa	Poisson's ratio	impact strength J
COPPER										
Manganese Bronze862 [B147-8B] {C86200}	655 (5)	331 (5)	20 (5)		180 Bhn (5) s		103 (5)	345 (1) v		16 (5) u
Yellow brass 858 [Z30A] {C85800}	380 (1) b	201 (1) b,p 207 (5)	15 (1) b		102 Bhn (1) 55 Rb (5)		105 (1)			54 (5) t
Bronwite	517 (5)	276 (5)	20 (5)		82 Rb (5) 119 Bhn (5) r		124 (5)			102 (5) t
OM metal	483 (5)	241 (5)	25 (5)		70 Rb (5) 80 Bhn (5) r		103 (5)			68 (5) t
A metal	462 (5)	283 (5)	10 (5)		145 Bhn (5) s		103 (5)			
White Tombasil	414 (5)	186 (5) p			70 Rb (5) 120 Bhn (5) s		110 (5)			

KEY TO NOTES ON MECHANICAL PROPERTIES

a. 6 mm diameter, die cast test specimen
b. typical for separately cast test bars, as cast
c. 500 kg load, 10mm ball, 30 seconds
d. F temper
e. T5 temper
f. 500,000,000 cycles
g. shear
h. as cast
i. modulus of rupture
j. 1% permanent set
k. reverse bending at 10^8 cycles
l. 10 mm sq ASTM unnotched specimen
m. Charpy 6.35 mm, unnotched
n. Charpy V-notch
o. rotating beam
p. at 0.5% extension under load
q. 0.2% offset unless otherwise noted
r. 500 kg
s. 3000 kg
t. Charpy unnotched
u. Izod
v. 0.1% permanent set
w. 10% permanent set
x. tension, unless otherwise noted
y. properties identical to AZ91B

C. Processing Properties

PROCESSING PROPERTIES OF DIE CASTING ALLOYS

alloy name commercial (ANSI) [ASTM] {UNS} <SAE>	recom. inj. temp. degrees C	recom. eject. temp. degrees C	recom. mold temp. degrees C	melting temp. degrees C	alloy cost $/lb
ALUMINUM					
typical data for most aluminum alloys	632-640 (8) 650 (9) 635-704 (1)	427-482 (8) 454 (9)	300 (14)	650-760 (1)	1 a
ZINC					
Zamak 3 Alloy 3 [AG40A] {Z33520} {L14400} <903>	410-413 (10) 420 (11) 393-427 (1)	220-250 (11)	180-230 (11) 200 (14)	387-500 (12)	1 a,b
Zamak 5 Alloy 5 [AC41A] {Z35530} {L14100} <925>	393-427 (1)			386-500 (12)	
Zamak 7 Alloy 7 <903>					
Alloy 16 ILZRO 16	460-470 (1)				

PROCESSING PROPERTIES OF DIE CASTING ALLOYS, CONT'D.

alloy name commercial (ANSI) [ASTM] {UNS} <SAE>	recom. inj. temp. degrees C	recom. eject. temp. degrees C	recom. mold temp. degrees C	melting temp. degrees C	alloy cost $/lb
ZA					
ZA-8 {Z35630}	416-458 (13) 450-600				1.02 a,c
ZA-12 {Z35840}	418-460 (13) 450-600			380-430 (1)	1.03 a,c
ZA-27 {Z25630}	419-502 (13) 537-593 (1) 450-600				1.07 a,c
MAGNESIUM					
[AZ91A] {M11910} <501>	620-675 (12) 677 (9)	400 (CB)	260 (9)	421 (1) 468-596 (12)	1.43 a
[AZ91B] {M11912} <501A>	650-695 (1)	440 (CB)			
AZ91D	f	f	f	f	f
[AM60A] {M10600} <501A>	660-695 (1)	460 (CB)			
[AS41A] {M10410}	620-675 (12)	400 (CB)		421 (1) 468-596 (12)	

PROCESSING PROPERTIES OF DIE CASTING ALLOYS, CONT'D.

alloy name commercial (ANSI) [ASTM] {UNS} <SAE>	recom. inj. temp. degrees C	recom. eject. temp. degrees C	recom. mold temp. degrees C	melting temp. degrees C	alloy cost $/lb
COPPER					
Silicon brass 879 [ZS331A] {C87900}	948 (5)	560-700 (5)	315 (5)	821-916 (6)	1.55 d
Silicon brass 878 [ZS133A] {C87800}	980-955 (1)			898-927 (6)	
Manganese Bronze865 [B147-8A] {C86500}					
Manganese Bronze862 [B147-8B] {C86200}					
Yellow brass 858 [Z30A] {C85800}	949 (5)		250-500 (5)	871-898 (6)	1.05 e
Bronwite					
OM metal					
A metal					
White Tombasil					

KEY TO NOTES ON PROCESSING PROPERTIES

a. costs obtained February 24, 1989
b. typical for all zinc alloys
c. truckload quantities
d. typical for contaminant-free proprietary Silicon Brass
e. typical for common-grade Yellow Brass
f. properties identical to AZ91B

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